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CHARLOTTENLUND

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ON THE NATURALLY OCCURRING ELECTROMAGNETIC NOISE CALLED AURORAL HISS

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5) Observations of the VLF Emission Hiss at 8 kc/s in Greenland 1964, Ionosphere Laboratory, The Technical University of Denmark, 1966.

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ABSTRACT

A wideband electromagnetic noise known as auroral hiss is observed at very low and low frequencies at ground-based stations and on satellites at high magnetic latitudes.

This noise is shown to be correlated to various geophysical phenomena as aurora, magnetic disturbances, sporadic E layers and absorption of cosmic radio waves. The correlations indicate a relationship between fluxes of low-energy electrons in the high latitude magnetosphere and generation of hiss. A direct correlation between hiss and low-energy electrons is observed from the Injun 3 satellite.

Observations of hiss from the ground and in space show that hiss is generated in the polar regions of the magnetosphere. The low-latitude boundary of these hiss zones seems to be consistent with the low-latitude boundary of the auroral oval.

A model for a region in space in which auroral hiss is believed to be generated is discussed, and it is shown that auroral hiss may be generated by incoherent Cerenkov radiation from electrons with energies of the order of 1 keV.

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I. INTRODUCTION

Naturally occurring electromagnetic noise at audible frequencies generated in the ionosphere or the magnetosphere is called VLF emissions. There are different types of noise classified according to their shape in a frequency-time spectrogram (Gallet, 1959), but they can all be characterized as either discrete noise, which has a clear structure in the spectrogram or hiss, which has no or very little structure and so resembles white noise. We shall here exclusively be dealing with hiss.

The study of VLF emissions in the plasma surrounding the earth is of great importance. The analysis of experimental data on emissions of different types detected on the ground or in the ionosphere, indicates the mechanisms of generation and radiation under different conditions, the character of interaction between the plasma, charged particle fluxes and electromagnetic waves. Such an analysis is also a good tool for studies of the plasma structure. For example can observation of cyclotron frequencies give information of particle masses and magnetic field strengths, and from measurement of the lower hybrid resonance the ionospheric composition and temperature can be deduced.

Hiss is observed in a very wide frequency range from approximately 1 kHz (McInnes, 1961) to 500 kHx (Jørgensen, 1968), but it does not seem to be the same noise phenomenon in this whole range as far as the mechanism of generation is concerned, as hiss below approximately 2 kHz mainly occurs during the day (McInnes, 1961 and Laaspere et al., 1964), while hiss above 2 kHz has its maximum occurrence in the evening and night (Jørgensen, 1966 a). A recording of a typical wide band hiss event is shown in Figure 1.

Although no detailed theory explaining the VLF emissions is developed so far, there seems to be agreement that the sources of the emissions must be found in the ionosphere or the magnetosphere (Helliwell, 1965). Sources outside the earth's magnetosphere have not been considered because the magnetosphere is supposed to be impenetrable for VLF energy coming from outer space. In the hypotheses for generation of VLF emissions the electromagnetic energy is believed to come from energetic particles in the ionosphere and the magnetosphere.

The amplitude of VLF emissions as measured in the ionosphere may be of the order of 10^{-12} W $m^{-2}Hz^{-1}$. However, even at this extreme value of amplitude, the energy density is many orders of magnitude lower than the measured energy fluxes of charged particle streams in the earth's outer ionosphere (Gurnett and O'Brien, 1964). Thus the kinetic energy of these particle streams appears a likely source of energy for the production of the emissions.

Mechanisms for conversion of the kinetic energy of the particles to electromagnetic energy can be divided in two main categories dependent on if the particles' longitudinal or transversal motion is the controlling factor.

Mechanisms which depend on the longitudinal motion include Cerenkov radiation and a kind of amplification similar to the one going on in a traveling wave tube. The particles' transversal motion in the earth's magnetic field is almost circular, and the radiation connected to it is of the cyclotron type.

When it so far not has been possible to make a final determination of the mechanism or mechanisms of generation, one of the reasons probably is the relatively limited knowledge one has of the occurrences of VLF emissions in time and space as well as the relation of VLF emissions to other geophysical phenomena, where especially a precise information concerning simultaneous occurrences of VLF emissions and energetic particles in the ionosphere and the magnetosphere is important.

In recent years the experimental knowledge of VLF emissions and energetic particles in the earth's upper atmosphere has increased considerably, and so there might be basis for a discussion of the suggested mechanisms on this new and better background.

In Chapter II a summary of the experimental knowledge of hiss will be given including its relation to other geophysical phenomena. On this foundation a model for the region in space in which hiss probably is generated will be discussed in Chapter III.

In Chapter IV hitherto suggested VLF mechanisms will be reviewed and in Chapter V one of these mechanisms (Cerenkov radiation) will be discussed in detail.

II. THE EXPERIMENTAL KNOWLEDGE OF HISS

A. HISTORICAL NOTES

The first observations of hiss seem to have been carried out in U.S.A. by Burton and Boardman (1933) who in the audible frequency range observed "a frying sound" which was closely correlated to a simultaneous occurrence of aurora. In England Eckersley (Storey, 1953) observed hiss at 5 kHz by means of a receiver connected to some big loop antennas in a direction finding system. Eckersley found that the noise came from the North.

After this nothing happened within the field until Storey (1953) published his work on whistlers. Storey observed hiss and used as the first this name. He showed that whistlers were propagating along the lines of force in the earth's magnetic field, and so he also opened the possibility for an explanation of the VLF emissions, as these possibly could be generated in the ionosphere or the magnetosphere and like whistlers propagate along the field lines down to the surface of the earth.

During IGY (International Geophysical Year) in 1957-58 several so-called whistler stations were established. They recorded during 2 min. per hour the VLF noise spectrum by means of a tape recorder. The setting up of these stations was inspired from Storey's work on whistlers, and it was also the whistlers who gained the greatest interest. However, a great amount of new knowledge regarding the VLF emissions was acquired on the same time, but almost exclusively about the discrete types like chorus.

Only few workers seem to have been interested in hiss. The reason for this is probably that hiss is very difficult to distinguish from amplifier and tape noise. Further, hiss is a typical polar cap phenomenon, and as only very few whistler-stations were situated at high latitudes, it is not very strange that a relatively scanty information was gathered in this way.

The first successful equipment to be designed, built and operated specially for observations of hiss - the so-called hiss recorder - was due to Ellis (1959). The hiss recorder is a device that carries out a continuous recording of hiss in a narrow frequency band. It consists of an antenna with preamplifier, a selective amplifier, a detector and a strip chart recorder (Jørgensen, 1966 b). The detector is a very important part of the system. It must be designed so it records hiss, the amplitude of which is varying relatively slow, and not the usually much more intense impulsive atmospheric noise. Such a discrimination is possible when the detector's charging time constant is of the order of several seconds and the discharge time constant of the order of 0,01 seconds. The knowledge of hiss has increased considerably since the introduction of the hiss recorder, because by means of it the rate of occurrence and the spectral density of the hiss bursts as well can be measured.

In the following the experimental results found by use of hiss recorders will be summarized.

B. SPECTRAL DENSITY VERSUS FREQUENCY

Only few measurements of the amplitude-frequency distribution of hiss have been carried out. Dowden (1962) examined the ground level intensities recorded at several spot frequencies between 125 Hz and 230 kHz during wideband bursts observed at Hobart. The observed spectral densities ranged from nearly 10^{-9} W $m^{-2}Hz^{-1}$ at 125 Hz to 10^{-19} W $m^{-2}Hz^{-1}$ at 230 kHz. However, he found that the spectral density above the ionosphere, deduced by subtracting the losses suffered in the ionosphere and below the ionosphere, showed a relatively flat spectrum at a level of the order of 10^{-10} W $m^{-2}Hz^{-1}$.

Gurnett (1966) found from measurements in space by the Injun 3 satellite between approximately 0.1 and 10 kHz that the frequency spectrum of auroral hiss is typically a flat noise spectrum with a distinct lower frequency cutoff of about 2 kHz.

Observations of hiss at very low and low frequencies carried out from Byrd Station in the southern auroral zone and from the polar orbiting satellite OGO 2 have been reported by the author (Jørgensen, 1968). It was found that the typical noise spectra observed from the ground (Figure 2) and in space (Figure 3) exhibit similar characteristics with a peak spectral density near 10 kHz, and the spectral density falling off at both sides of the peak with about 20 db/decade. Maximum spectral densities observed on the ground and in space are about 10^{-14} and 10^{-12} W $m^{-2}Hz^{-1}$ respectively, but usually the peak spectral densities are one or two orders of magnitude lower. The lower spectral densities observed on the ground compared to those in space are probably due to absorption and/or internal reflection in the ionosphere.

C. SPECTRAL DENSITY VERSUS LATITUDE

The author (Jørgensen, 1966 a) studied ground based recordings of hiss from 13 stations in both hemispheres ranging in magnetic latitudes (Mayaud, 1960) from 38° to 89°. It was found that the maximum spectral density in the frequency range 4-9 kHz was about 10^{-14} W $m^{-2}Hz^{-1}$ from the auroral zones and polewards, while the maximum spectral density from the auroral zones and equatorwards was decreasing from the value mentioned with approximately 10 db/1000 km. (Figure 4). It was concluded that hiss came down through the ionosphere over the polar caps and then propagated to lower latitudes between the ionosphere and the earth.

This idea seems to be in agreement with results obtained by Ondoh and Isozaki (1965). They have simultaneously recorded hiss at 5 kHz at Moshiri (34.0° N, 206.4° E; geomag.) and at Hiraiso (26.2° N, 206.3° E; geomag.) and found that the spectral density was about 10 db higher at Moshiri compared to Hiraiso. They conclude that the difference in spectral densities is in agreement with the expected theoretical loss of propagation at propagation from North towards South.

The fact that the fieldstrength of atmospheric radio noise which originates from thunderstorms decreases with increasing latitude, and the spectral density of hiss increases with increasing latitude opens the possibility that the smallest detectable radio signal which can be received at high latitudes is not determined by the atmospheric noise level, but by the hiss level. This question was investigated by the author (Jørgensen, 1965), and it was shown that the intensity of hiss can exceed the atmospheric radio noise level, and so determine the smallest detectable radio signal at low and very low frequencies. Further, that the disturbing effect of hiss is greater in auroral regions than at lower latitudes.

Existing predictions of radio noise (C.C.I.R., 1964) do not take account of hiss as an interfering noise, and the predictions should therefore be used with caution for the low and very low frequencies in polar regions.

Preliminary investigations showed that possible interference of radio communications caused by hiss will not occur very often and that the duration of the interference will be of the order of minutes.

Increases in the intensity of atmospheric noise on 20 kHz during auroral displays have been reported (Gherzi, 1960), and it is possible that the observed noise may have been hiss.

D. CORRELATION BETWEEN HISS AND OTHER GEOPHYSICAL PHENOMENA

1. Magnetic Activity.

Ellis (1959) found by hiss observations from Camden during sunspot maximum, that all large magnetic storms were accompanied by hiss storms that often lasted 48 hours. On the average the hiss began 6.5 ± 2.7 hours after the sudden commencement. Most observed hiss bursts were not distinctly correlated with magnetic activity, and these bursts always appeared at night. Wide-band hiss (2-29 kHz) was observed only during great magnetic storms.

From a comparison of the hiss activity per day recorded at Godhavn (October 1962 through January 1963) with magnetic disturbance as measured by A_p, the author (Jørgensen, 1964) found a definite positive correlation in which the time of maximum occurrence is delayed 1 to 3 days with respect to the time of maximum magnetic disturbance. In both sets of data the sun's 27 days rotation period is seen (Figure 5).

Harang and Larsen (1965) have demonstrated that the moderate positive disturbances in the horizontal component of the geomagnetic field appearing early in the night at an auroral zone station very often are accompanied by hiss bursts, and that sudden and strong magnetic disturbances which appear as so-called negative bays in the horizontal component near magnetic midnight usually are accompanied by strong hiss emissions.

2. Aurora.

An association between hiss and auroral phenomena have been found. Statistical correlations have been established, both between subvisual auroras and hiss (Duncan and Ellis, 1959) and between visual auroras and hiss (Martin et al., 1960; Jørgensen and Ungstrup, 1962; Morozumi, 1962). Hiss that is associated with aurora usually appears at frequencies above 4 kHz but on occasion the low-frequency limit may fall as low as 600 Hz (Helliwell, 1965).

Details of the relation between hiss and aurora were explored in a study carried out at the South Pole during the dark months of 1960 (Morozumi, 1962). It was found that hiss does not seem to be characteristic of all auroras, but is closely associated with auroral arcs and bands. Hiss was associated with two kinds of arc and band auroras. The first is the display of arcs and bands without prominent development, and the second type consists of arcs and bands followed by breakups.

A comparison of all-sky photometer white light recordings and all-sky camera photographs with the hiss recordings (Morozumi, 1962) showed that the peak in hiss coincided with the development of homogeneous arcs and bands in the aurora. However, when the aurora broke up and arrived at the zenith, the total light intensity increased, but the hiss intensity decreased, possibly because of increased absorption of the VLF energy in the D region of the ionosphere.

3. Sporadic E.

An investigation of 8 kHz hiss recordings and ionograms from Narssarssuaq in Greenland (Jørgensen, 1964), have shown that a hiss burst, which can last from a few minutes to several hours, always occurred together with sporadic E. The most common E_s type in connection with hiss was E_{sa}, next E_{sf} and E_{sr} and, more seldom E_{sd} and E_{sl}.

Hiss was never observed together with E_{ss}. It was found that the peaks of the critical frequencies of the sporadic E layers were delayed about 10 minutes compared to the peaks in hiss intensity. (Figure 6).

4. Cosmic Radio Wave Absorption.

Morozumi (1962) has shown that when the ray type of aurora occurred near UT midnight, ionospheric absorption was high and hiss was usually absent.

Harang and Larsen (1965) found at Tromsø during periods of small ionospheric absorption, less than approximately 1 db at 28 MHz, a positive correlation between increases of the spectral density of hiss and enhancements of the absorption. During periods of strong absorption, greater than 5 db, the correlation was negative.

5. Energetic Particles.

By means of the Injun 3 satellite Gurnett (1966) found that on the high latitude side of the 40 keV trapping boundary, where polar hiss usually occurs, intense fluxes of soft electrons often are accompanied by hiss. It was found that the correlation between hiss and intense fluxes ($I > 2.5 \times 10^7/cm^2$ ster sec) of electrons ($E > 10$ keV) is dependent on the exponential folding energy E_o. The correlation is very good (84 o/o) for E_o from 3 to 4 keV but poor for larger E_o values.

The author (Jørgensen, 1966 a) found that very intense electron fluxes ($E > 40$ keV), the so-called electron spikes observed by the Alouette 1 satellite (McDiarmid and Burrows, 1965) at latitudes above the region where the boundary of the outer Van Allen radiation zone normally occurs, was observed in the same regions in a magnetic latitude - magnetic time coordinate system as were the most intense hiss bursts. A remarkable correlation between the daily hiss activity at Godhavn and the occurrence of electron spikes seen by the Alouette 1 satellite during a period of 33 days in 1963 was found, and it was suggested that the generation of hiss is closely connected to these very intense particle streams.

E. THE HISS ZONES

The author (Jørgensen, 1966 a) studied the general shape and location of the hiss zones which are defined as the regions on the earth illuminated by hiss propagating down through the ionosphere. The hiss zones - there is one in each of the two polar regions - are not fixed in a coordinate system rotating with the earth, but in a magnetic latitude - local magnetic time coordinate system.

The hiss zones are found to be apparently the same as the zones of auroral precipitation. So they are approximately circular shaped with their centers situated close to the magnetic midnight meridian some few degrees from the geomagnetic poles. Hiss is not observed equally often everywhere in these zones as there is a maximum of the occurrence at about 70° magnetic latitude shortly before magnetic midnight. (Figure 7).

While hiss at about 70° latitude mainly is observed in the evening and until shortly after magnetic midnight, the occurrence of hiss around 80° latitude is somewhat more evenly distributed, and it is possible at this latitude to observe hiss at any time of the day.

Very little investigation of hiss has been carried out close to the magnetic poles, but the observations made so far seem to show that hiss is a relatively rare phenomenon at the very high latitudes.

The normal low latitude boundary of the hiss zone on the night side of the earth is located around 65° magnetic latitude consistent with the normal low latitude boundary of the auroral oval.

It is shown (Jørgensen, 1966 b) that the general shape of the hiss zone does not change in any pronounced way during the year. The maximum activity on the surface of the earth seems to be higher in the winter compared to the summer, which possibly is due to the higher ionospheric absorption in the summer.

At quiet and disturbed conditions respectively the extent of the hiss zone, and the hiss activity as well, is very different. During quiet conditions the hiss activity is small, and hiss is only observed in a relatively small region close to magnetic midnight, while both the hiss activity and the extent of the hiss zone is much bigger in disturbed periods. It is remarkable that the region of maximum hiss activity, which at quiet and moderately disturbed days is located about 1 hour before magnetic midnight, on disturbed days occurs about 3 hours before magnetic midnight, but still on the same latitude around 70°.

If this means that the generation of hiss in the ionosphere or the magnetosphere during disturbed conditions takes place at some other place in space than it does during quiet conditions, or if this change of the location for maximum observation on the ground of hiss is caused by an increased ionospheric absorption near magnetic midnight is not known.

The characteristic shape and location of the hiss zone as found from the above mentioned ground based observations is very similar to a hiss zone found by Gurnett (1966) from measurements with the Injun 3 satellite (Figure 8). Gurnett studied the occurrence of radio noise from 5.5 to 8.8 kHz exceeding a magnetic field strength of 3×10^{-10} $gamma^2$ Hz^{-1} and found that when hiss occurred, it almost always occurred during local afternoon and evening from 12 to 24 magnetic local time. The range of magnetic latitude, in which hiss typically occurred was about 10° wide and centered on 77° at magnetic local noon, decreasing to 72° at 23 magnetic local time.

III. THE REGION OF HISS GENERATION

Concerning the region in space in which hiss is generated, the experimental work carried out so far seems to be consistent with the following picture: Hiss is generated in the auroral regions of the magnetosphere and the mechanism of generation is closely connected to very intense fluxes of electrons with energies of the order of a few keV. Since the energy flux of the energetic electrons is many orders of magnitude larger than the electromagnetic energy flux (Gurnett and O'Brien, 1964) it seems reasonable to assume that hiss is generated by the energetic electrons.

Any mechanism of generation depends on plasma parameters such as gyrofrequency and plasmafrequency of the thermal electrons and ions as well as the distribution function of the energetic electrons. Therefore we will try to determine these parameters and thus make a model for the region in the magnetosphere in which hiss is believed to be generated.

The energetic particles spiral along the lines of force of the earth's magnetic field, and the energy of a whistler-mode wave propagates mainly in the direction of the magnetic field as long as the wave frequency is not too close to the electron gyrofrequency (Helliwell, 1965). Therefore it seems fair to assume that the generation takes place in a tube of lines of force which hits the surface of the earth at auroral latitudes, where the hiss activity is maximum. A suitable field line along which we can carry out the investigation would be one which hits the surface of the earth at 70° geomagnetic latitude.

A. GYROFREQUENCY

The main magnetic field of the earth can be approximated by the field due to a magnetic dipole placed at the center of the earth. In the magnetosphere, the dipole model of the earth's magnetic field is a reasonably good one out to at least 5 earth radii, and so we will consider the field line along which we want to know the electron gyrofrequency as one belonging to a dipole field.

For a dipole field we have the following expressions for determination of the electron gyrofrequency f_{He} (Helliwell, 1965):

$$f_{He} = f_{Heq}\left(\frac{R_o}{R}\right)^3 (1 + 3 \sin^2 \emptyset)^{\frac{1}{2}} \tag{3.1}$$

$$R = R_o \frac{\cos^2 \emptyset}{\cos^2 \emptyset_o} \tag{3.2}$$

Where f_{Heq} is the electron gyrofrequency at the equator at the surface of the earth = 880 kHz, R_o is the mean earth radius = 6370 km, R is the geocentric radius, $\emptyset$ is the geomagnetic latitude and $\emptyset_o$ is the geomagnetic latitude at R_o. By combining the two equations we find

$$f_{He} = f_{Heq}\left(\frac{R_o}{R}\right)^3 \left[1 + 3\left(1 - \frac{R}{R_o} \cos^2\emptyset_o\right)\right]^{\frac{1}{2}} \tag{3.3}$$

which gives the electron gyrofrequency along a given field line as a function of geocentric distance. In Figure 9 the gyrofrequency along the field line hitting the surface of the earth at 70° geomagnetic latitude is shown.

B. PLASMAFREQUENCY

The electron plasmafrequency f_o is given by

$$f_o^2 = \frac{Ne^2}{4\pi^2 m\varepsilon_o} \tag{3.4}$$

Where N is the electron density, e and m the electronic charge and mass, respectively, and ε_o the electric permittivity of free space.

While electron density measurements have been carried out at auroral latitudes from the bottom of the ionosphere and up to about 3000 km (Hagg, 1967), we more or less have to guess about the electron densities above 3000 km at these latitudes.

Jespersen, et al. (1966) made electron density measurements in the lower ionosphere from Andenes in Norway close to the zone of maximum occurrence of aurora by means of rocket-borne Faraday rotation experiments. They found electron densities of the order of $10^4 - 10^5$ cm^{-3} at 100 km near magnetic midnight during moderate auroral disturbances in connection with which hiss is generally observed on the ground.

Ionograms from Godhavn and Narssarssuaq, in Greenland, obtained during periods of strong hiss activity in the winter and spring months of 1964, show that the maximum plasmafrequency in the F-layer varies between 2 and 4 MHz. A typical value is 3 MHz which we can use in our model ionosphere.

The information on electron densities in the polar magnetosphere from the F-layer maximum and up is obtained mainly from topside soundings provided by the Alouette 1, Alouette 2 and Explorer 2o satellites.

Concerning the electron density at an altitude of 1000 km (Thomas et al., 1966), there exists a monotonic decrease with latitude from a few times 10^4 electrons/cm^3 at mid-latitudes to as low as 10^3 electrons/cm^3 near the magnetic poles, with daytime higher than nighttime values. However, superimposed on this latitudinal distribution are prominent large-scale minima or "troughs." Of more importance, perhaps, is the observation that large electron density maxima or "peaks" occur at latitudes greater than those at which the troughs are found. At these maxima, the electron density often reaches a magnitude exceeding that observed at mid-latitudes. The peak to trough ratio of the electron densities at the height of the satellite may exceed 25 to 1. Both the troughs and peaks have spatial magnitudes of a few hundred km. In addition small scale irregularities exist in space and time.

Unfortunately, as we do not have small-scale electron density information obtained from a satellite simultaneous with hiss intensity measurements, it is rather difficult to say what a typical electron density is at an altitude of about 1000 km at auroral latitudes during a hiss event, but a figure of 1×10^4 electrons/cm^3 may be representative.

Between 1000 km and 10,000 km we will assume that the plasmafrequency decreases with approximately the same rate as the gyrofrequency. This so-called gyrofrequency model has been given a theoretical basis by Dowden (1961). Above 10,000 km the plasmafrequency is likely to decrease asymptotically to the plasmafrequency of interplanetary space, which is of the order of 10^4 Hz. The plasmafrequency model as described above is shown in Figure 9.

C. ION COMPOSITION

Work by Storey (1956), Hines (1957) and others has shown that ions have an effect on propagation of VLF waves in the magnetosphere. Therefore we will include the composition of positive ions in the model magnetosphere we will use in connection with the Cerenkov radiation calculations. To the author's knowledge little is known about ion composition in the high latitude magnetosphere, so we will use information obtained at mid-latitudes and assume that such results may be representative of the ion composition at auroral latitudes. From whistler studies, Beghin (1966) found the composition of oxygen, helium and hydrogen ions as a function of altitude. We will use the data shown in Beghin's Figure 8a. Our resulting derived ion composition model is shown in Figure 1o.

D. ENERGETIC PARTICLES

As mentioned above, simultaneous observations by the Injun 3 satellite (Gurnett, 1966) of electrons with energies larger than 10 keV and of hiss showed that hiss almost always was observed when the satellite passes through very intense streams of auroral electrons. The observations indicated that electrons with energies less than 10 keV play an important role in the production of hiss.

A rather detailed investigation of the auroral electron spectrum above 1 keV has been carried out by Evans (1966) who flew channel multiplier detectors on two rockets through auroras over Fort Churchill. Both rockets were launched around magnetic midnight during moderately disturbed conditions, which seem to have been typical hiss conditions. It is not known if any VLF observations were made during the rocket launchings, but we will assume that the electron spectra observed by Evans (1966) are representative of the electron fluxes which are correlated to hiss.

An average of the spectrums observed by Evans is shown in Figure 11. The pitch angle distribution for electrons with energies below 4 keV was reported to be nearly isotropic. Also in Figure 11 the density of the energetic electrons in the energy intervals indicated near the bottom of the figure is shown. The density of electrons with energies between 1 and 16 keV is seen to be 8 electrons/cm^3.

In the calculations of the total power produced by the Cerenkov process, which will be discussed below, it will be assumed that the density of the energetic particles is the same everywhere in the flux tube, which we consider as the region of generation of hiss. Furthermore it will be assumed that the pitch angle distribution is isotropic.

These are probably fair assumptions due to the fact that electron spectra, measured in the dark hemisphere of the magnetosphere at much larger distances from the earth (8 - 20 earth radii) (Frank, 1967) than those we are going to consider (1 - 5 earth radii) are very much like the spectra observed by Evans in the lower ionosphere. The electron fluxes reported by Frank (1967) are only about one order of magnitude below the fluxes observed by Evans (1966), and likewise the pitch angle distribution is close to isotropic.

IV. THEORIES OF VLF EMISSIONS

During the last decade several mechanisms have been proposed as explanations of VLF and LF emissions, which are believed to originate in the earth's magnetosphere, but none of the mechanisms has ever been proved. Reviews of VLF emission theories have been given by Helliwell (1965; 1966).

As pointed out by Sturrock (1962), energetic particle fluxes are just one of a number of possible sources of radio noise in the vicinity of the earth; nevertheless, the facts of the correlations of VLF emissions with various geophysical phenomena and the presence of energetic particle fluxes in the ionosphere during these disturbed times have led most workers to postulate that the emissions are produced by direct energy conversion from particle kinetic energy to electromagnetic wave energy.

The particle-flux hypotheses of VLF emissions generation can be divided into two types, the first being those which explain the emissions as being due to single energetic particles radiating either incoherently or coherently in the ionospheric plasma, and the second type being those which explain the emission as being due to a plasma instability caused by the collective interaction between the particle flux and the plasma.

In the single particle hypothesis, the emissions are created through the conversion of kinetic energy to electromagnetic energy by means of Cerenkov radiation or cyclotron radiation.

In the plasma instability hypothesis, the originally incoherent Cerenkov or cyclotron radiation given off by the particles under certain circumstances induces a self-modulation of the particle beam leading to a coherent, exponentially growing radiation. The plasma instability effects in general occur when the particles experience a resonance interaction with a perturbing wave, i.e., the particles "see" either a doppler-shifted perturbation wave frequency approximately equal to their gyrofrequency (the cyclotron resonance) or a doppler-shifted perturbation-wave frequency approximately equal to zero (the Cerenkov resonance). When one of these resonance conditions is fulfilled, it is possible for an instability to arise in the beam-plasma system with the subsequent emission of radiation.

In the following a short review of the various proposed VLF mechanisms will be given.

A. SINGLE PARTICLE MECHANISMS

1. Cerenkov radiation

Cerenkov radiation is emitted by particles whose velocity is greater than the phase velocity of electromagnetic waves in the medium. Since for whistler mode propagation in the ionosphere the refractive index is usually large compared with unity, it is apparent that particles with relatively low velocity may satisfy the Cerenkov condition.

Electromagnetic signals from a single particle are radiated coherently at an angle Θ to the direction of the longitudinal velocity of a particle, if the following condition is satisfied:

$$\frac{c}{\mu} = v_{\parallel} \cos\Theta \tag{4.1}$$

where

μ = real part of wave refractive index
$v_{\parallel}$ = longitudinal particle velocity
c = velocity of light in vacuum

Ellis (1957) was the first to suggest that Cerenkov radiation might be the emission mechanism responsible for low frequency broadband hiss. As a result of his work, Ellis found that the calculated intensity of Cerenkov radiation was not sufficient to explain the observed intensities of hiss. However, he originally considered only incoherent radiation, and later (Ellis, 1959) pointed out that the assumption that the distance between the energetic particles was small compared to a wavelength would lead to a coherent radiation, the intensity of which was sufficient to explain the observations of auroral hiss.

Many other authors have considered the application of Cerenkov radiation to the generation of VLF signals in the ionosphere (Ellis, 1960; Ondoh, 1961, 1962, 1963; Gershman and Ugarov, 1961; Benediktov et al., 1962; Clemmow, 1962; McKenzie, 1963; Mansfield, 1964; Liemohn, 1965), but nobody found the energy density for incoherent Cerenkov radiation high enough to explain the observed energy density of the emissions.

2. Cyclotron Radiation.

Cyclotron radiation from energetic particles in the outer ionosphere was apparently first mentioned in the literature as a mechanism for VLF emission by Ellis and MacArthur independently in 1959. At that time, Ellis (1959) proposed that narrowband 4 kHz hiss which he had observed might be due to cyclotron radiation from energetic electrons at a distance of 6 earth radii (geocentric). On the other hand, MacArthur (1959), in reference to the chorus phenomena, noted that groups of energetic protons traveling down the magnetic field lines toward an observer and emitting energy through the cyclotron process would, as a result of the doppler shift, appear to be radiating at a much higher frequency, which could lie in the VLF range.

For cyclotron radiation from electrons, the refractive index in the whistler mode is infinite. However, the electron cyclotron radiation may be doppler shifted to a frequency at which it may propagate in the whistler mode. The frequency radiated f is given in terms of the longitudinal velocity $v_{\parallel}$ (Brice, 1964) by

$$v_{\parallel} = \frac{c}{\mu}\,\frac{f-f_H}{f} \tag{4.2}$$

Since no frequencies higher than the local gyrofrequency will propagate, only energy emitted as the electron travels away from the observer will be detected by him as normal radiation.

When protons are considered, it is necessary to have recourse to the anomalous doppler effect (Ginzburg and Frank, 1947; Ginzburg, 1960) in order to produce observable radiation. In an electronic plasma at whistler mode frequencies, a proton gyrating about the ambient magnetic field lines will excite the propagating magneto-ionic mode only when its velocity along the field lines is greater than the phase velocity of a propagating wave at some given frequency. If the velocity of a proton satisfies this condition, then the electromagnetic waves radiated by the particle will be circularly polarized with a rotational sense opposite to that of the motion of the particle about the ambient magnetic field lines. This phase reversal phenomena due to doppler shift is commonly known in the Soviet literature as the anomalous doppler effect. For a radiating proton the effect obeys the relation (Brice, 1964).

$$v_{\parallel} = \frac{c}{\mu} \frac{f_H + f}{f} \tag{4.3}$$

where f is the radiated wave frequency as seen by a stationary observer.

Following the suggestion by MacArthur (1959) that emissions might result from doppler shifted cyclotron radiation from protons, Murcray and Pope (1960a, 1960b) computed the emission shapes (hooks) that might be expected.

Santirocco (1960) computed the energy density that might be expected for the doppler shifted cyclotron radiation and suggested it was insufficient to explain VLF emissions. Murcray and Pope (1961) replied that if the radiation from a large number of protons added coherently, the energy output might be increased by a sufficiently large factor. However, no mechanism was suggested for organizing the particles to produce coherent radiation.

As a variation on the theory of MacArthur, Dowden (1962b) suggested that VLF emissions could be produced by doppler shifted cyclotron radiation from bunches of electrons. In this process, the electrons were taken as moving away from the observer, resulting in the reception of a wave frequency. An advantage of this process over that of MacArthur was that the radiated cyclotron power for single electrons could be much greater than that for protons, since the radiated power for singly charged particles of the like velocity is inversely proportional to the square of the particle mass (Panofsky and Phillips, 1955). Dowden attempted to show that radiated waveforms predicted on the basis of his theory corresponded quite closely to some of the forms of discrete VLF emissions which had been observed. This point was disputed by Brice (1962), who demonstrated that the predicted waveform did not in reality agree with experiments. In order to reconcile the predicted and observed intensities of emissions, it was necessary for Dowden to assume that the electron group emits radiation coherently. Although the fact was not stated by Dowden, coherence in a group of electrons emitting cyclotron radiation requires that the particles be bunched in phase space rather than in physical space, and Brice (1963) proposed a method whereby this phase bunching might be accomplished.

B. PLASMA INSTABILITY MECHANISMS

When one of the resonance conditions (4.1), (4.2), or (4.3) is fulfilled for a beam of particles, it is possible for collective effects to develop which will lead to a growth of initial perturbations in the beam-plasma system (Bell, 1964). In general the fulfillment of one of the resonance relations is a necessary condition that an instability should arise; however, it is not a sufficient condition. The sufficiency must be established by demonstrating that the initial distribution function for the particles in the beam-plasma system has the proper behaviour at the resonance point (Bell, 1964).

The instability, once it is shown to exist, can be classified as being either of the convective variety or the nonconvective variety (Sturrock, 1958). An instability is termed convective if the growing disturbance is propagated away from the point of origin. An instability is termed nonconvective if the disturbance grows in amplitude and extent while always including the original point of origin.

In general when a resonance is fulfilled as the beam and the perturbing wave move in the same direction, the instability, if produced, is convective. On the other hand, motion of the beam and wave in opposite directions while a resonance condition is fulfilled leads only to a nonconvective instability. Thus the resonance conditions (4.1) and (4.3) are indicative of convective instability, while condition (4.2) is indicative of a nonconvective instability.

1. Traveling-Wave Amplification.

At approximately the same time that Ellis was presenting his ideas on Cerenkov produced hiss, Gallet and Helliwell (1957, 1959) independently presented an analogous hypothesis, namely that VLF emissions were produced by selective traveling-wave amplification of low-level ambient noise through a collective interaction between particle streams and the outer ionospheric plasma. It was suggested that the ambient plasma in the ionosphere or magnetosphere might act in a manner analogous to the slow-wave circuit of a conventional traveling-wave amplifier, so that a beam of electrons might produce amplification of ambient noise in the medium. The criterion for amplification is essentially the same as that for the Cerenkov condition, in that the velocity of the beam must be just greater than that which matches the phase velocity of the wave.

Gallet and Helliwell were able to show in addition that their mechanism resulted in the production of waveforms which were quite similar to many of the discrete emissions observed upon the ground. A weak point in the Gallet-Helliwell theory was the fact that these authors had presented only a phenomenological picture of the hypothesized interaction and had not calculated the intensities of emissions which could be expected, nor investigated the exact nature of the coupling mechanism between the waves and the streaming particles. Nevertheless, the succes of the theory in explaining the observed VLF waveforms led a number of workers to attempt to investigate the theory more thoroughly.

Bell and Helliwell (1960) and Adachi and Mushiake (1962) considered a cold electron beam in a cold ambient plasma. They found a growing wave for nonzero wave-normal angles and also that the computed growth rates for suitable values of parameters were significant. However, Barrington (1960) and Kimura (1961) stated that the growing mode was a space-charge wave and that the whistler-mode signal neither grew nor decayed in the presence of the beam. In addition, Barrington (1960) examined the coupling between the growing mode and the whistler-mode and suggested that the coupling arising from a change in plasma frequency of 1 kHz/km or less was insignificant.

Dowden (1962) suggested that if the amplification became very large, a situation might develop analogous to an overloaded amplifier so that a broadband signal (hiss) could be generated by this mechanism. However, he assumed that the emitted signals had zero wave normal angle, and it is generally agreed that for zero wave normal angle the whistler mode is not exited.

Kimura (1961) and Maeda and Kimura (1962a, 1962b) identified the nongrowing mode in the traveling wave hypothesis with the whistler mode, and suggested that for this reason an electron beam could not produce emissions. They found that the corresponding mode for a proton beam did show growth characteristics. Using proton-beam densities of ten particles per cubic centimeter, they obtained significant growth rates. The resonance condition for the velocity is the same as that given in Eq. (4.3), Maeda and Kimura (1962a, 1962b) suggested that the growth rates obtained by them were probably inadequate to amplify the ambient noise in the medium to a level comparable to that observed in VLF emissions.

2. The Transverse-Resonance Plasma Instability.

Another collective interaction is based on transverse resonance between the wave and gyrating electrons (Brice, 1963; Hansen, 1963). Consider a frame of reference in which the longitudinal particle velocity is zero, resonance occurs when the doppler shifted wave frequency observed in this frame of reference is the particle gyrofrequency. In this frame, both the particles and the electric and magnetic fields of the wave rotate about the static magnetic field at the same rate, and in the same sense. The resonance condition is given in Equation (4.2). It has been found that under certain conditions realizable in the magnetosphere this transverse resonance can lead to an instability that might account for the generation of VLF emissions (Bell and Buneman, 1964). In this mechanism the emitted radiation encounters new electrons moving into the interaction region because the stream and wave velocities are oppositely directed. Thus modification of the particle distribution can be produced by the emitted radiation itself. The disturbance in this case is non-convective and is characteristic of oscillators whereas in the traveling-wave mechanism, the disturbance is convective and is characteristic of amplifiers (Sturrock, 1958). The strong feedback inherent in the nonconvective instability might permit significant changes in the distribution of the incoming particles and lead to large changes in the frequency and amplitude of the disturbance. Furthermore, the duration of the emission would be limited only by the supply of particles and the form of the emitted radiation.

V. GENERATION OF HISS BY CERENKOV RADIATION IN THE WHISTLER MODE

As mentioned above the first mechanism ever suggested as an explanation of VLF emissions was the Cerenkov process (Ellis, 1957), but Ellis, Liemohn (1965) and others concluded that the total energy produced by an incoherent Cerenkov radiation process was several orders of magnitude too low to explain the observed power densities.

In view of the better information we have today of the magnetospheric environment as well as the occurrence in space and the intensity of VLF and LF emissions compared to the situation a few years ago, it is clear that there may exist several reasons for the discrepancies between theory and observations in earlier attempts to explain emissions by Cerenkov radiation. For example no data on the thermal electron density above the F2 layer maximum were available when Ellis did his work in 1957, and only little was known about the population of energetic particles in the magnetosphere.

Liemohn (1965) derived expressions for the power radiated by an electron spiralling in a magnetoplasma, and estimated the total power produced by energetic electrons in a tube of lines of force. The total power from an incoherent process was calculated by the expression

$$P_{total} = P_e \cdot N_e \cdot V \tag{5.1}$$

Where P_e is the average emitted power per electron, N_e the density of the energetic electrons and V the volume of the tube. Assuming the direction of energy flow was strictly along the field lines, the calculated power was compared to an observed power and it was found that the observed power exceeded the calculated power by seven orders of magnitude. This difference is much too large for the following three reasons. 1) The observed power with which the calculated power was compared was claimed to be 10^{-10} W m^{-2}Hz^{-1}, but in a recent paper Gurnett (1966) reports the maximum spectral density observed by Injun 3 during the satellite's 10-months lifetime to be about

10^{-12} W $m^{-2}Hz^{-1}$, and preliminary results obtained by the VLF experiment in the OGO 2 satellite, which are reported in this paper, are in agreement with this. 2) While the noise was observed at latitudes where the magnetic shell parameter L (McIlwain, 1961) is about 7 and higher (Gurnett and O'Brien, 1964), the tube of lines of force, the volume of which was used in the total power calculation, was located by Liemohn at L = 3, and so the volume used was much too small. 3) The density of the energetic particles was taken to be 0.1 cm^{-3}, but densities of electrons with energies between 1 and 10 keV observed in the auroral zone have been found to be almost 2 orders of magnitude higher (Evans, 1966).

In view of the factors discussed above, the models used in earlier works considering Cerenkov radiation as a mechanism for VLF and LF emissions probably were unrealistic, and so a new attempt is considered worthwhile.

A. CONDITIONS FOR CERENKOV RADIATION

A Cerenkov wave is generated by a charged particle moving in a plasma, if the component in the wave normal direction of the particle's longitudinal velocity equals the phase velocity of the wave. This means that Cerenkov radiation only can occur at frequencies for which the refractive index is greater than one, that is: 1) at frequencies above the plasma cutoff and below the upper hybrid plasma resonance; and 2) at frequencies below the plasma cutoff and below the electron cyclotron resonance. This can be seen, for example, by consideration of the α, β diagram (Allis, Buchsbaum and Bers, 1963).

Auroral hiss is believed to propagate in the whistler mode, and in this paper we will exclusively consider Cerenkov radiation in this mode, that is to say in the second of the two frequency domains mentioned above.

Considering the variation of the electron gyrofrequency as a function of altitude in the model region of generation (Figure 9), it is clear that the maximum frequency at which Cerenkov radiation can be generated in the whistler mode is equal to the electron gyrofrequency at the bottom of the ionosphere, that is about 1.6 MHz. High frequencies can only be generated in a relatively short flux tube close to the earth, while low frequencies can be generated in a long flux tube. For example radiation at 1.0 MHz can only be generated below an altitude of 1000 km, while radiation frequencies at 10 kHz can be generated at all altitudes up to about 25,000 km.

A qualitative discussion of the properties of Cerenkov radiation in the whistler mode can be carried out using a technique shown by McKenzie (1963). This technique is demonstrated in Figure 12, where the four main configurations of whistler mode refractive index surfaces are drawn for frequencies between the ion cyclotron frequency f_{Hi} and the electron cyclotron frequency f_{He}.

In order to find out if Cerenkov radiation is generated at a certain frequency by a particle with a certain longitudinal velocity $v_{\parallel}$, the appropriate refractive index surface is drawn, and a line of length $c/v_{\parallel}$, where c is the free space velocity of light, is drawn from the origin of the refractive index surface diagram, parallel to the magnetic field direction $\overline{B}$. If a right triangle with two of the sides being $c/v_{\parallel}$ in the magnetic field direction and the refractive index in the wave normal direction can be constructed as shown in Figure 12, a Cerenkov wave will be emitted at the frequency in question. That this condition is equivalent to the Cerenkov condition mentioned above is easy to see from the triangle, where $\mu \cos\Theta = c/v_{\parallel}$. The ray direction can also be found from the figure, because we know that the ray $\overline{R}$ is perpendicular to the refractive index surface.

As $c/v_{\parallel}$ is inversely proportional to the longitudinal particle velocity it is seen that for $f_{Hi} < f \lesseqq f_{LHR}$, where f_{LHR} is the lower hybrid resonance frequency, Cerenkov radiation can only be generated by particles with longitudinal velocities larger than a certain velocity $v_{\parallel min}$, whereas for $f_{LHR} < f < f_{He}$ Cerenkov radiation can occur only when the longitudinal particle velocity is less than a certain maximum velocity $v_{\parallel max}$. Considering the frequency range $f_{LHR} < f < \frac{1}{2} f_{He}$, it is seen from Figure 12 c that there exists a certain particle velocity range in which two different waves will be emitted at the same frequency.

B. POWER PRODUCED BY CERENKOV RADIATION

Expressions for the power produced by Cerenkov radiation from a charged particle spiralling in a cold magnetoplasma have been derived by Mansfield (1964) and by Liemohn (1965). As we will consider only Cerenkov radiation in the magnetospheric plasma, which has a temperature corresponding to an energy less than 1 eV, generated by particles with energies greater than 1 keV, we will assume that the cold plasma theory is valid for this study.

According to Mansfield (1964) (whose results are in agreement with those of Liemohn (1965)), the power produced by Cerenkov radiation from a single particle expressed in W/Hz is given by the following equation:

$$dP/df = \sum_{j=1}^{2} q^2 2\pi f \Big[\beta_\perp^2 T_{11} J_1^2(L_o) + \beta_\parallel^2 T_{33} J_o^2(L_o)$$

$$- 2\beta_\perp \beta_\parallel T_{13} J_1(L_o)\, J_o(L_o)\Big] \Big/ \varepsilon_o v_\parallel \, (B_n^2 - 4C_n\varepsilon_1)^{\frac{1}{2}} \Big|_{\mu=\mu_j} \quad (5.2)$$

where

$$\beta_\perp = v_\perp/c \qquad \beta_\parallel = v_\parallel/c \quad (5.3),\ (5.4)$$

$$B_n = (c/v_\parallel)^2 (\varepsilon_3 - \varepsilon_1) + \varepsilon_2^2 - \varepsilon_1^2 - \varepsilon_1\varepsilon_3 \quad (5.5)$$

$$C_n = (c/v_\parallel)^2 (\varepsilon_1^2 - \varepsilon_2^2 - \varepsilon_1\varepsilon_3) + \varepsilon_3 (\varepsilon_1^2 - \varepsilon_2^2) \quad (5.6)$$

$$\mu_{1,2}^2 = \Big[-B_n \pm (B_n^2 - 4C_n\varepsilon_1)^{\frac{1}{2}} \Big] \Big/ 2\varepsilon_1 \quad (5.7)$$

$$\cos\theta = 1/\beta_\parallel \mu \quad (5.8)$$

$$T_{11} = \varepsilon_1\varepsilon_3 - \varepsilon_1\mu^2 \sin^2\theta - \varepsilon_3\mu^2\cos^2\theta \quad (5.9)$$

$$T_{13} = \varepsilon_2\mu^2 \sin\theta\cos\theta \quad (5.10)$$

$$T_{33} = \varepsilon_1^2 - \varepsilon_2^2 - \varepsilon_1\mu^2 + (\mu^4 - \varepsilon_1\mu^2)\cos\theta \quad (5.11)$$

$$L_o = (f/f_{He})\beta_\perp \mu \sin\theta \quad (5.12)$$

In these expressions q is the charge of the electron, $v_{\perp}$ is the particle's transverse velocity, $\varepsilon_1, \varepsilon_2$ and ε_3 are the dielectric tensor elements with the ions (Figure 10) included, θ is the wave normal angle relative to the earth's magnetic field, J_o and J_1 are the Bessel functions of first kind and zeroth and first order respectively and L_o is the argument of the Bessel functions. MKS units are used.

Using Mansfield's expression the power produced at different frequencies between 1 kHz and 1 MHz by Cerenkov radiation from a spiralling electron has been calculated as a function of particle energy, pitch angle and altitude in the model region of noise generation discussed earlier in this paper. The results of some of these calculations are shown in Figure 13 for the case of a 1 keV electron with 0° pitch angle. It is seen that the highest powers are generated at low altitudes in the upper end of the frequency band we are studying, whereas the low frequency radiation mainly is generated at high altitudes.

At 1, 2 and 5 kHz peaks are found at about 8000, 5000 and 3000 km respectively. The peaks occur where the wave frequency is equal to the lower hybrid resonance f_{LHR}. In the case study shown in Figure 13, Cerenkov radiation is also generated at frequencies below f_{LHR}, but the power is several orders of magnitude below the power generated above f_{LHR}, and so it is not shown in the figure. As a function of particle energy only, the power is found to vary inversely proportional with the square root of the particle energy in the energy range studied, that is for energies between 1 and 20 keV.

C. CALCULATION OF HISS SPECTRUM

We will now attempt to calculate the total power produced by Cerenkov radiation in the model region of generation, that is, in a flux tube with the cold plasma properties and the energetic electron characteristics as discussed in Section III. The cross sectional area of the tube at the bottom of the ionosphere is chosen to be 1 m^2, and we will calculate the total radiation produced below an altitude of 26,000 km. This last figure is rather arbitrary and mainly chosen because it is realized that the percentage deviation of the values of plasma- and gyrofrequency in the model ionosphere (Figure 9) from the values in a real ionosphere probably is increasing with altitude, and that great errors thus may be made by including calculations at very high altitudes in the total power calculation. Also at about that altitude the cold plasma density is comparable to the energetic particle density, which means that the average temperature of the plasma is too high for the cold plasma theory to be valid.

For the purpose of the numerical integration of all the radiation produced, the flux tube is divided into 14 regions, the altitude boundaries of which are indicated in the top of Figure 13, and it is then assumed that the power produced in any of these regions by an electron with a certain energy and pitch angle is the same everywhere in the region, but usually different from one region to another. The total volume of the tube of lines of force is found to be $1.1 \times 10^9 m^3$.

As mentioned above, the power generated is inversely proportional to the square root of the particle energy, with all other parameters being constant, but for ease of numerical power integration, we will take the power to be independent of energy within each of the 5 energy intervals shown in Figure 11. Finally, because the power generated has been found to be rather insensitive to pitch angle variations except for large pitch angles, we will assume that the power is independent of pitch angle variations.

With these assumptions the total power generated at a certain frequency now can be calculated by the following expression:

$$
\begin{aligned}
\frac{dP}{df} = {} & V_1 \cdot \left[N(\Delta E_1) \cdot \frac{dP}{df}(\Delta E_1, V_1) + \ldots + N(\Delta E_5) \cdot \frac{dP}{df}(\Delta E_5, V_1) \right] \\
& + V_2 \cdot \left[N(\Delta E_1) \cdot \frac{dP}{df}(\Delta E_1, V_2) + \ldots + N(\Delta E_5) \cdot \frac{dP}{df}(\Delta E_5, V_2) \right] \\
& - - - - - - \\
& + V_{14} \cdot \left[N(\Delta E_1) \cdot \frac{dP}{df}(\Delta E_1, V_{14}) + \ldots + N(\Delta E_5) \cdot \frac{dP}{df}(\Delta E_5, V_{14}) \right]
\end{aligned}
\tag{5.13}
$$

where V_n is the volume of the n'th region of the flux tube (Figure 13), $N(\Delta E_n)$ is the density of energetic electrons in the n'th energy interval (Figure 11) and $\frac{dP}{df}(\Delta E_n, V_m)$ is the power produced by an electron belonging to the energy interval ΔE_n in region V_m.

The total power generated in the model region we are considering has been calculated at a number of frequencies between 1 kHz and 1 MHz by the method described. The results obtained for the frequency range between 1 and 100 kHz may be found from Figure 14 by multiplying the ordinate by 1 m^2 which represents the cross sectional area of the base of the flux tube. The results of the calculations between 0.1 and 1 MHz are not shown in the figure, but if plotted they would appear as a continuation of the "straight line" between 10 and 100 kHz.

In order to explain the noise spectral densities observed on the ground and from satellites (Figures 2 and 3), the total calculated energy, or at least a great part of it must propagate along the field lines and cross the 1 m^2 area bottom of the model region of noise generation. Whether this is likely to happen or not will be discussed as follows.

There are two different mechanisms by which electromagnetic energy propagating in the whistler mode may be guided in the direction of the static magnetic field. One is called magnetoionic guiding. It is due to the anisotropy of a homogeneous plasma introduced by the presence of a static magnetic field. The other mechanism of guiding is called ducting, which can occur when field aligned irregularities are present.

As the magnetoionic guiding is far too ineffective in order to explain the guiding needed in our case, and further because there is strong evidence that field aligned irregularities exist in the auroral ionosphere, we will here only consider ducting as a possible mechanism for the guiding of the Cerenkov radiation-produced energy down to the bottom of the ionosphere.

Ducting of whistler-mode energy has been studied theoretically by several workers using different techniques. Smith et al. (1960) used ray theory, Voge (1962), Booker (1963) and Walker (1966) used mode theory, and Adachi (1965 and 1966) applied a full wave theory to the problem. We will not discuss here the duct theories in any detail, but just note that the different workers in the field agree that a complete trapping of waves may take place depending on the type of irregularity.

It is amazing that the enhancement or depression of the electron density needed for trapping to occur is found to be only a few percent or in some cases even less than one percent.

As mentioned in Section II, it has been observed by means of the Explorer 20 satellite (Lund et al., 1967) that the auroral precipitation which in this paper is considered as the source of high latitude hiss, produces large electron density fluctuations within the latitudinal region containing the precipitation, and that the electron number density is increased at all altitudes between the F-layer maximum and the height of the satellite (about 1000 km). Very steep latitudinal electron density gradients are also found by Calvert (1966) to occur in the topside F-layer at high latitudes. The gradients are often larger than 60 °/₀ km^{-1} within the auroral zone.

It is not known if these irregularities extend along the field lines up to altitudes of several thousand km, but if they do, it seems very likely that wave guiding can take place.

If the field aligned irregularities are produced at altitudes below 1000 km, the diffusion velocity v along the field lines can be estimated using the expression $\frac{1}{2} mv^2 = 3/2\ kT$, where m is the ion mass and T the ion temperature. Ion temperatures of about 6000 $^{\circ}K$ have been measured by Knudsen and Sharp (1967) in the auroral zones, and using this figure and the mass of a proton a diffusion velocity up to an altitude of 10,000 km in about 15 minutes. Because the ion temperature probably is higher inside the region of auroral precipitation, where the electron density is high, it might be expected that the scale height would be larger here, and that the magnitude of the horizontal electron density gradient will increase with altitude.

Support of the hypothesis of ducting is provided by noise observations reported by Heyborne (1966). By means of the OGO 2 satellite noise at 17.8 kHz was regularly observed at auroral latitudes, and very often the noise amplitude changed by more than 40 db, while the satellite was moving only a few degrees in latitude. These observations indicate that the satellite moved in and out of the ducts in which the noise was trapped.

Thus there is strong evidence of ducting of whistler mode energy in the auroral ionosphere, and we will therefore assume that a large amount of the energy generated by the Cerenkov process is propagating in a flux tube down to the bottom of the ionosphere. Under the assumption of perfect guiding of the energy calculated above, the spectral density of the noise in the lower ionosphere would be as shown in Figure 14. It is seen that the noise spectrum in Figure 14 is rather similar to the noise spectra observed on the ground (Figure 2) and from a satellite (Figure 3).

The difference of about two orders of magnitude between the maximum observed spectral density (10^{-12} W $m^{-2}Hz^{-1}$) and the maximum calculated spectral density (10^{14} W $m^{-2}Hz^{-1}$) is not considered serious for the following reasons: The calculated spectrum is produced by electrons with energies above 1 keV only, because the present knowledge of auroral electrons with energies below 1 keV is poor. Inclusion of electrons with energies below 1 keV in the calculation of the noise spectrum will increase the spectral density. Furthermore, the observed spectral densities probably are too high, because the longitudinal refractive index has been used in the derivation of the observed spectral densities (Jørgensen, 1968). With wave normal angles other than zero, the refractive index will increase, and the spectral density will therefore decrease.

VI. CONCLUSIONS

A. SUMMARY AND CONCLUSION

Observations of wideband noise emissions in the VLF and LF ranges carried out from the ground at high latitudes in both hemispheres and from the polar orbiting satellite OGO 2 have been reported. These noise emissions are known as "auroral hiss". As a possible mechanism of hiss generation the Cerenkov radiation from energetic particles in auroral regions of the magnetosphere has been studied.

The results of this research may be summarized as follows:

1) Simultaneous direct observations of hiss at 8 kHz and of aurora have shown that a positive correlation exists between the two phenomena. The intensity of the hiss has shown second-to-second and minute-to-minute variations similar to those of the intensity of light in, and the activity of, the aurora. In the periods of observation great activity of aurora was never observed without occurrence of intensive hiss, and intensive hiss never occurred when aurora was absent.

2) Hiss events recorded at an auroral latitude station are found to be closely connected to the occurrence of sporadic E layers. The most common E_s types in connection with hiss are E_{sa}, E_{sf} and E_{sr}. The hiss peak intensities are observed of the order of 10 minutes before the maximum frequencies reflected from the sporadic E layers. The observations indicate that hiss and sporadic E layers are created by the same kind of energetic particles.

3) Observations by the Alouette 1 satellite of very intense fluxes of electrons with energies above 40 keV at latitudes higher than the boundary of the outer radiation belt have shown that these fluxes are very well correlated to ground-based hiss observations both in space and in time. It is therefore suggested that these very intense electron fluxes are responsible for, or at least closely connected with, the generation of hiss. Owing to the positive correlation between

hiss activity and high-latitude electron fluxes, which again are correlated with the intensity variations in the outer radiation belt, it would appear to be possible to monitor, from the ground, high-intensity electron fluxes in the polar regions and intensity variations in the outer radiation belt.

4) By comparison of hiss recorded at two ground stations with predictions of atmospheric radio noise, it is shown that the intensity of hiss can exceed the expected atmospheric radio noise level at low frequencies, and also that the disturbing effect of hiss is greater in auroral regions than at lower latitudes.

Preliminary investigations have shown that possible interference of radio communications caused by hiss will not occur very often and that the duration of the interference will be of the order of minutes.

However, more measurements, especially around a few hundred kHz, have to be carried out before a clear picture of the interfering effect of hiss on radio communication is obtained.

5) Observations of hiss in the frequency range 4-9 kHz made at 13 stations in both hemispheres have shown that hiss is generated in certain zones. Apparently these zones are the same as the zones of auroral precipitation and so they are approximately circular, with their centers close to the magnetic midnight meridian some few degrees from the geomagnetic poles. Hiss is not observed equally often everywhere in these zones; there is a maximum of the occurrence at about 70° magnetic latitude shortly before magnetic midnight. Hiss seems to be a rare phenomenon at the very highest latitudes close to the geomagnetic poles.

The shape and location of the hiss zone does not change significantly as a function of local seasons, but the dependency of the degree of geomagnetic disturbance is clear, as the extent of the hiss zone is much smaller during quiet periods than during disturbed periods. Further, the region of maximum hiss activity, which during quiet periods is located at about 70° magnetic latitude about 1 hour before magnetic midnight, is occurring about 3 hours before magnetic midnight during disturbed periods.

6) From observations of wideband high latitude noise emissions in the VLF and LF ranges carried out from Byrd Station in the southern auroral zone and from the polar orbiting satellite OGO 2, it is found that the typical noise spectra observed from the ground and in space exhibit similar characteristics with a peak spectral density near 10 kHz, and the spectral density falling off at both sides of the peak with about 20 db/decade. Maximum spectral densities observed on the ground and in space are about 10^{-14} and 10^{-12} W $m^{-2}Hz^{-1}$ respectively, but usually the peak spectral densities observed are one or two orders of magnitude lower. The lower spectral densities observed on the ground compared to those in space are probably due to absorption and/or internal reflection in the ionosphere.

7) Cerenkov radiation in the whistler mode from electrons with energies of a few keV in the high latitude magnetosphere has been studied, and it is found that a calculated noise spectrum as produced by an incoherent Cerenkov process is comparable in magnitude and shape to observed noise spectrums.

It is concluded that the emission known as auroral hiss may be generated by incoherent Cerenkov radiation from electrons with energies of the order of a few keV.

This result is in contrast to earlier work by other workers and is due to the improved model of generation used in this study.

B. SAMMENFATNING OG KONKLUSIONER

I nærværende rapport berettes om observationer af bredbåndede støjemissioner der forekommer i VLF og LF frekvensområderne. Observationerne er foretaget fra jorden på høje breddegrader både på den nordlige og den sydlige halvkugle samt fra den polare satellit OGO 2. Disse støjemissioner er kendt som "nordlys hiss". Som en mulig genereringsmekanisme for hiss er Cerenkov stråling fra energetiske partikler i magnetosfærens nordlysregioner specielt undersøgt.

Arbejdets resultater er følgende:

1) Samtidige direkte observationer af hiss på 8 kHz og af nordlys har vist, at der eksisterer en positiv korrelation mellem de to fænomener. Variationer i hissets aktivitet svarer nøje til variationer i nordlysets lysstyrke og aktivitet. I observationsperioderne blev et meget aktivt nordlys aldrig observeret uden at der samtidig forekom intensivt hiss, og intensivt hiss forekom ikke under fravær af nordlys.

2) Hiss begivenheder observeret fra en station i nordlysegnene har vist sig at være tæt korreleret med forekomster af sporadiske E lag. De mest almindelige E_s typer som observeres i forbindelse med hiss er E_{sa}, E_{sf} og E_{sr}. Hissets maksimale intensiteter blev observeret omkring 10 minutter før de maksimale frekvenser der reflekteres fra de sporadiske E lag. Observationerne antyder, at hiss og sporadiske E lag produceres af samme slags energetiske partikler.

3) Observationer fra Alouette 1 satelliten af meget intense elektron fluxe med elektronenergier større end 40 keV foretaget på breddegrader der ligger højere end den ydre grænse af det ydre strålingsbælte har vist, at disse elektron fluxe er stærkt korreleret med jordbaserede hiss observationer såvel i sted som i tid. Det foreslås derfor, at de meget intense elektron fluxe er ansvarlige for eller i det mindste nært knyttet til genereringen af hiss. På grund af den positive korrelation mellem hiss aktivitet og elektron fluxe på høje breddegrader og endvidere den positive korrelation mellem disse elektron fluxe og variationer i partikelintensiteten i det ydre strålings-

bælte synes der at være en mulighed for fra jorden at overvåge tilstedeværelsen af intensive elektron fluxe i den polare magnetosfære og intensitetsvariationer i det ydre strålingsbælte.

4) Ved sammenligning af hiss registreret på to jord-stationer med forudsigelser af atmosfærisk radiostøj er det vist, at intensiteten af hiss kan overstige det forventede niveau af atmosfærisk radiostøj ved lave frekvenser, og endvidere at hissets forstyrrende virkning er større i nordlysområder end på lavere breddegrader. Foreløbige undersøgelser har vist at forstyrrelser af radio kommunikation forårsaget af hiss ikke vil forekomme ret ofte, og at forstyrrelsernes varighed kun vil vare nogle minutter. Imidlertid bør flere målinger - især omkring nogle få hundrede kHz - foretages før man kan få et klart billede af hissets forstyrrende virkning på radio kommunikation.

5) Observationer af hiss i frekvensområdet 4-9 kHz fra 13 stationer beliggende på middel og høje breddegrader såvel på den nordlige som sydlige halvkugle har vist at hiss genereres i visse zoner. Tilsyneladende er disse zoner de samme som dem hvori nordlyset forekommer, og de er derfor tilnærmelsesvis cirkulære med centrene nær den magnetiske midnatsmeridian og nogle få grader fra de geomagnetiske poler. Hiss observeres ikke lige ofte overalt i disse zoner idet der er en maksimal forekomst på omkring 70° magnetisk bredde kort før magnetisk midnat. Hiss synes at være et sjældent fænomen på de allerhøjeste breddegrader nær de geomagnetiske poler.

Formen og beliggenheden af hiss zonen ændres ikke af betydning i løbet af skiftende årstider, men afhængigheden af graden af magnetiske forstyrrelser er klar, idet hiss zonens udstrækning er meget mindre i rolige perioder end i forstyrrede perioder. Endvidere forekommer området med maximal hiss aktivitet, som i rolige perioder findes på ca. 70° magnetisk bredde og ca. een time før magnetisk midnat, ca. tre timer før magnetisk midnat i forstyrrede perioder.

6) Fra observationer på høje breddegrader af hiss i VLF og LF områderne foretaget fra Byrd Station i sydlyszonen og fra den polare satellit OGO 2 er det fundet, at de typiske frekvensspektre observeret fra jorden og fra satelliten udviser lignende karakteristika med en

maksimal spektraltæthed nær 10 kHz og med spektraltætheden faldende til begge sider fra maksimet med ca. 20 db/dekade. De maksimale spektraltætheder der er observeret fra jorden og i rummet er henholdsvis omkring 10^{-14} og 10^{-12} W $m^{-2}Hz^{-1}$, men sædvanligvis er de observerede maksimale spektraltætheder een eller to størrelsesordener mindre. De lavere spektraltætheder der observeres på jorden sammenlignet med de i rummet målte skyldes sandsynligvis absorption og/eller indvendig reflektion i ionosfæren.

7) Cerenkov stråling i whistler udbredelse fra elektroner med energier omkring nogle få keV i magnetosfæren på høje breddegrader er undersøgt, og det er fundet, at et beregnet støjspektrum produceret ved en inkoherent Cerenkov proces er sammenligneligt med observerede støjspektra i størrelse og form. Det konkluderes, at emissionen der kendes som nordlys hiss kan være genereret ved inkoherent Cerenkov stråling fra elektroner med energier af størrelsesorden nogle få keV. Dette resultat der er i modstrid med andres tidligere arbejder skyldes den forbedrede genereringsmodel der er anvendt her.

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ILLUSTRATIONS

Figure

1. Auroral hiss, Byrd Station, July 8, 1965. Amplitude (arbitrary units) as function of frequency and universal time.

2. Auroral hiss, Byrd Station, August 3, 1966. Spectral density as function of frequency and universal time.

3. Auroral hiss observed by OGO 2, November 12-23, 1965. Each dashed line corresponds to one pass of the satellite through a noise region, and the endpoints of a line represent the spectral densities measured at two frequencies simultaneously.

4. Maximum spectral densities versus latitude of hiss measured on the ground in the frequency range 4 - 9 kHz.

5. Correlation between magnetic activity and hiss.

6. Simultaneous occurrences of hiss bursts and sporadic E in Narssarssuax, October 5, 1962.

7. Contour map of the 8 kHz hiss zone on moderately disturbed days in 1964 drawn in a magnetic latitude - local magnetic time coordinate system. The contours surround regions in which hiss bursts with spectral densities above 1×10^{-15} W $m^{-2}Hz^{-1}$ occur in a given percentage of the hourly intervals.

8. Frequency of occurrence of VLF hiss with intensity exeeding 3×10^{-10} $gamma^2 Hz^{-1}$ (After Gurnett, 1966).

9. Electron plasma-frequency and gyrofrequency as functions of altitude in the model region of hiss generation.

10. Positive ion composition as function of altitude in the model region of hiss generation.

Figure

11. Flux and density as functions of energy of auroral electrons believed to generate hiss.

12. The Cerenkov radiation condition in the whistler domain studied by use of refractive index surfaces. Cerenkov radiation is generated by a particle with longitudinal velocity $v_{\parallel}$ if a line perpendicular to the magnetic field direction $\overline{B}_o$ and with distance $c/v_{\parallel}$ from the center of the refractive index surface cuts the refractive index surface. Both the wave normal direction and the ray direction $\overline{R}$ is found by the construction.
For $f_{LHR} < f < \frac{1}{2} f_{He}$ two waves with the same frequency may be generated.

13. The power generated at Cerenkov radiation by an electron with energy 1 keV and pitch angle 0^o at frequencies between 1 kHz and 1 MHz as a function of altitude in the model region of generation.

14. Theoretical hiss spectrum in the lower ionosphere produced by Cerenkov radiation in the model region of generation.

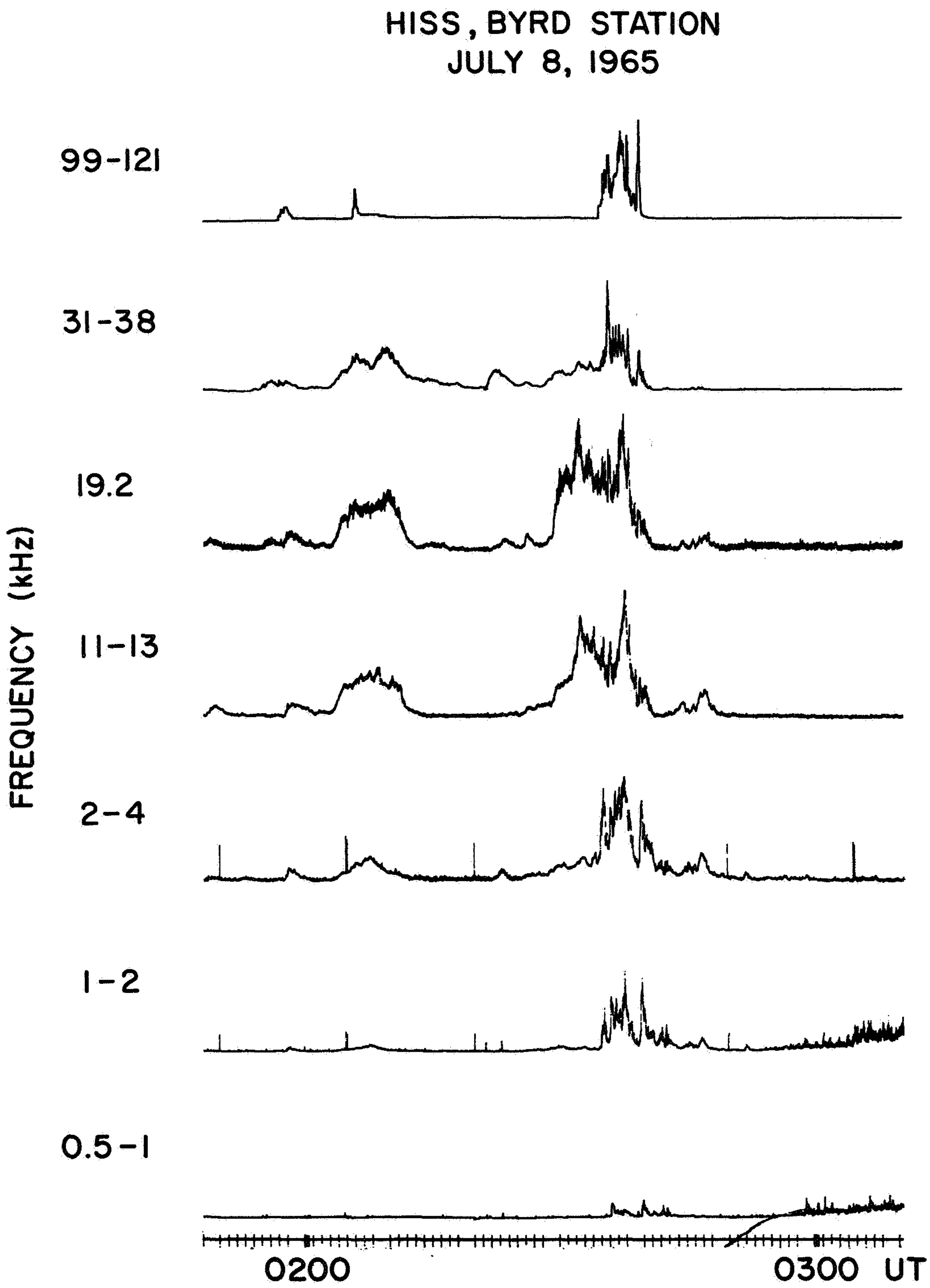
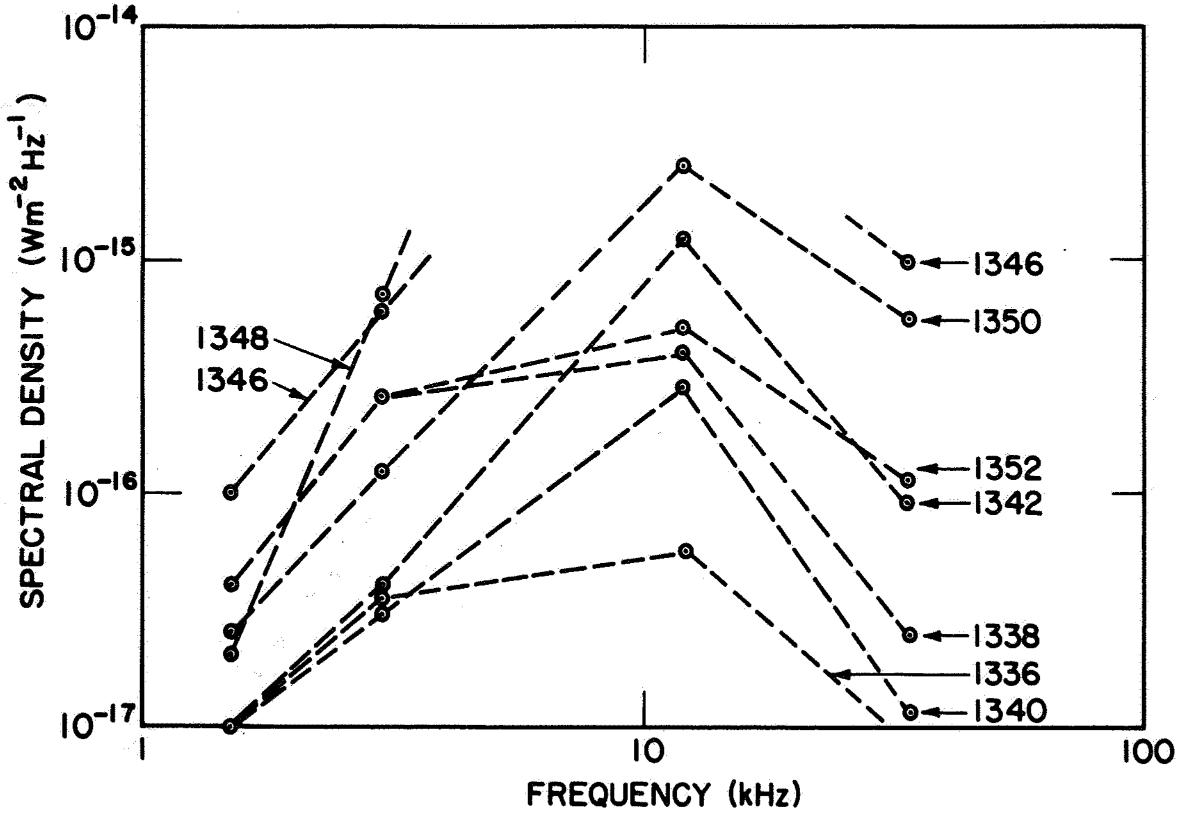
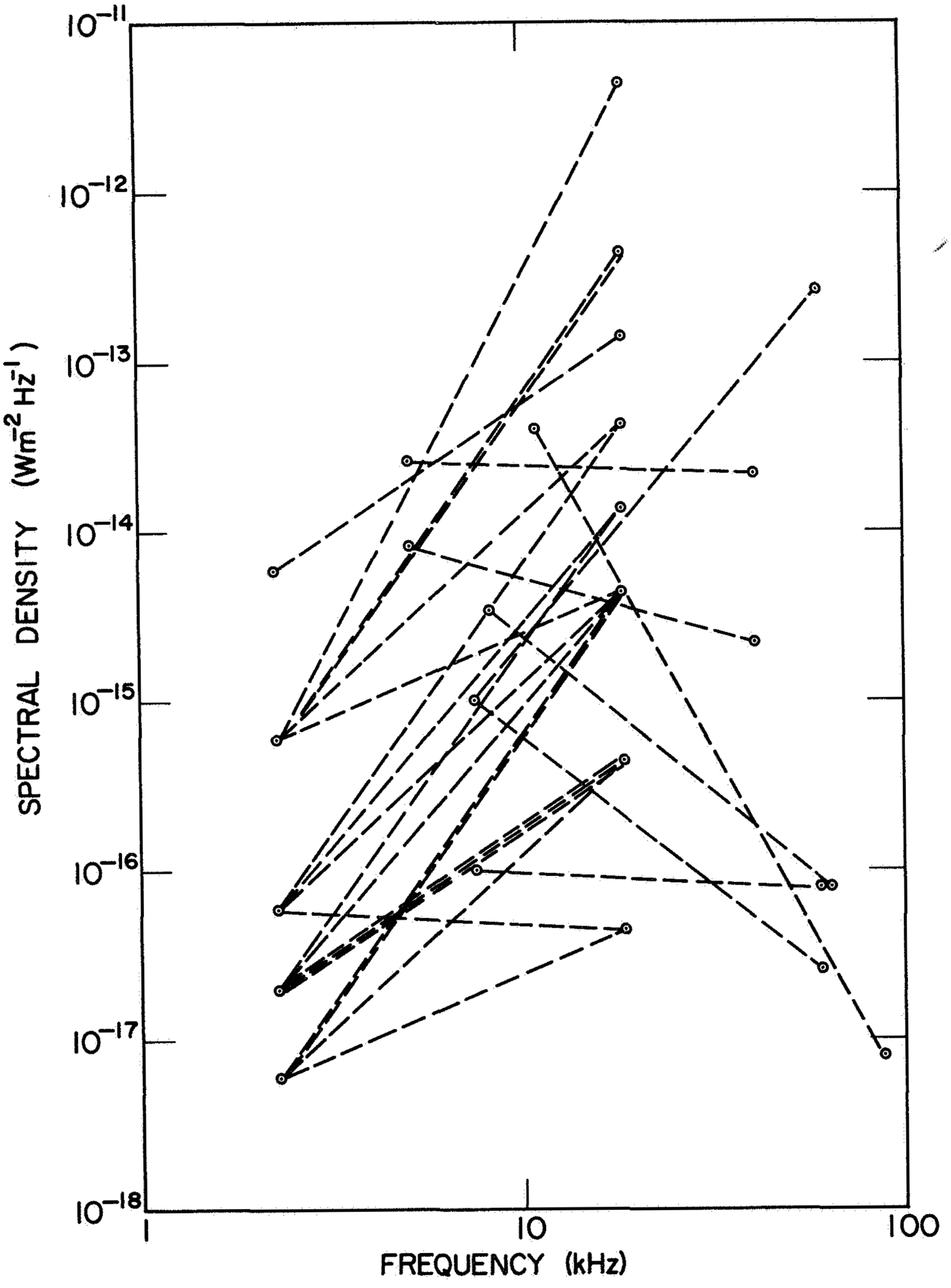

HISS, BYRD STATION
JULY 8, 1965
FREQUENCY (kHz)
99-121
31-38
19.2
11-13
2-4
1-2
0.5-1
0200
0300 UT

Figure 1



SPECTRAL DENSITY ($Wm^{-2}Hz^{-1}$)
10^{-14}
10^{-15}
10^{-16}
10^{-17}
1
10
100
FREQUENCY (kHz)
1348
1346
1346
1350
1352
1342
1338
1336
1340

Figure 2



10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
SPECTRAL DENSITY ($Wm^{-2}Hz^{-1}$)
1
10
100
FREQUENCY (kHz)

Figure 3

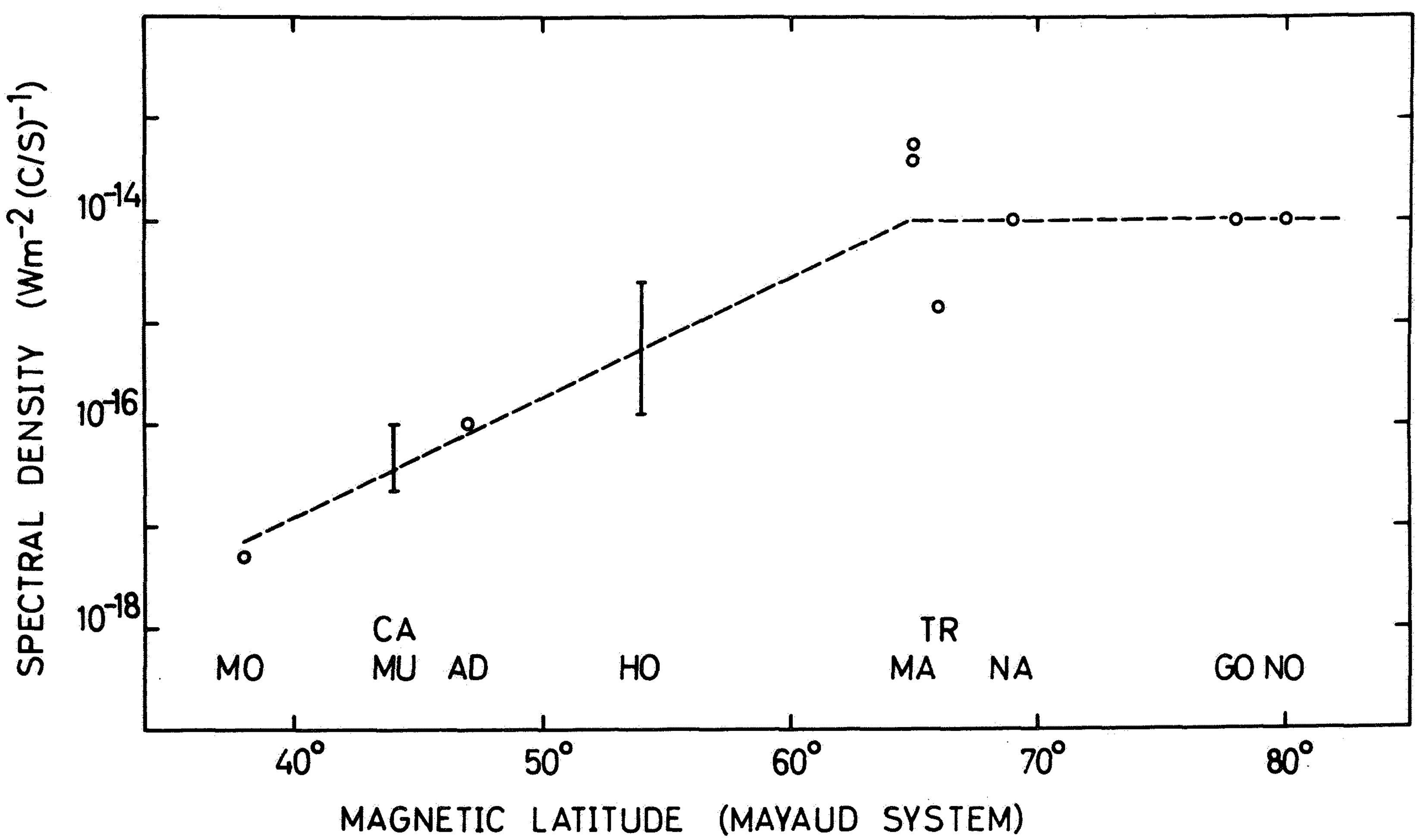

SPECTRAL DENSITY (Wm-2 (C/S)-1)
10-14
10-16
10-18
MO
CA
MU
AD
HO
TR
MA
NA
GO NO
40°
50°
60°
70°
80°
MAGNETIC LATITUDE (MAYAUD SYSTEM)

Figure 4

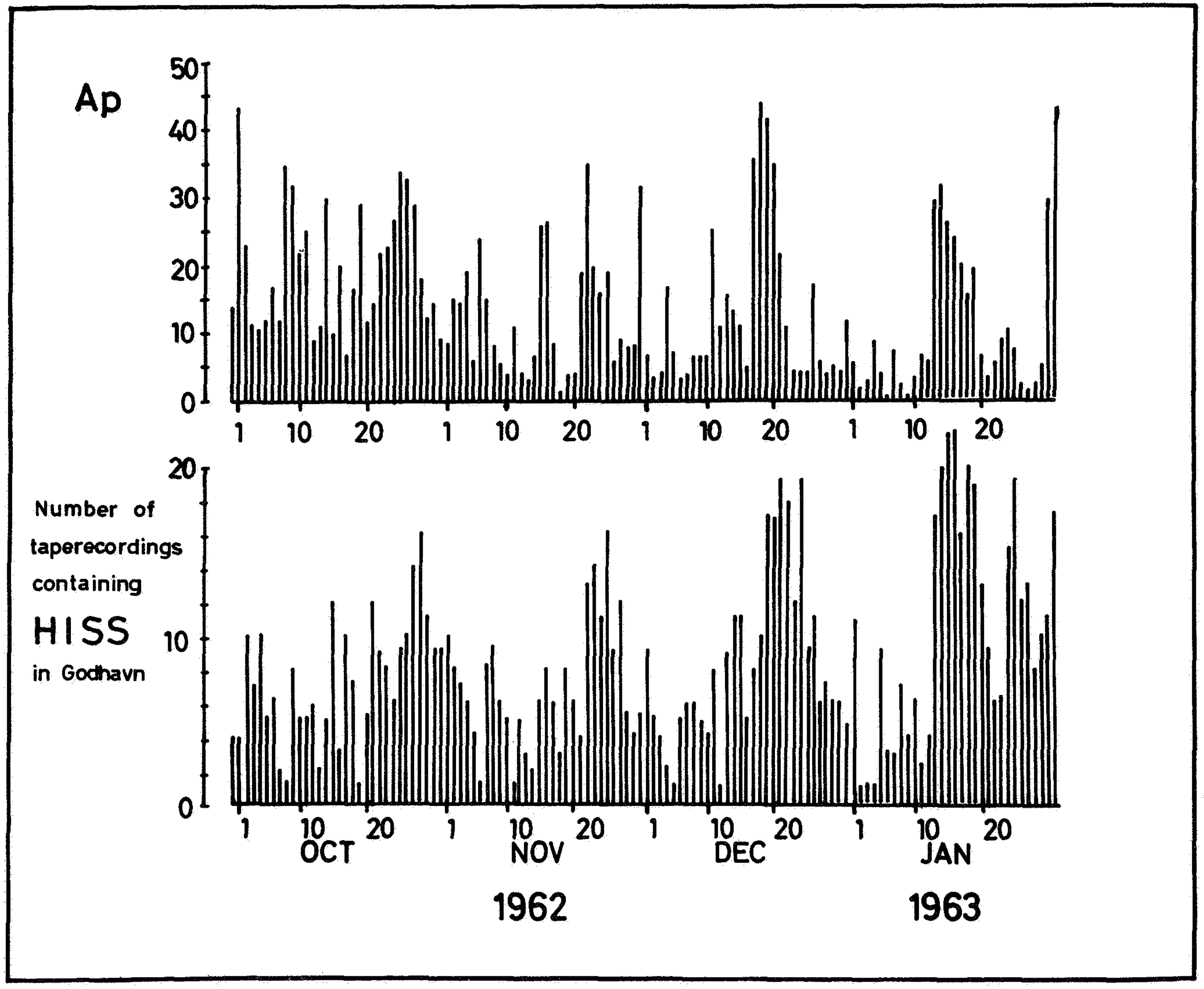
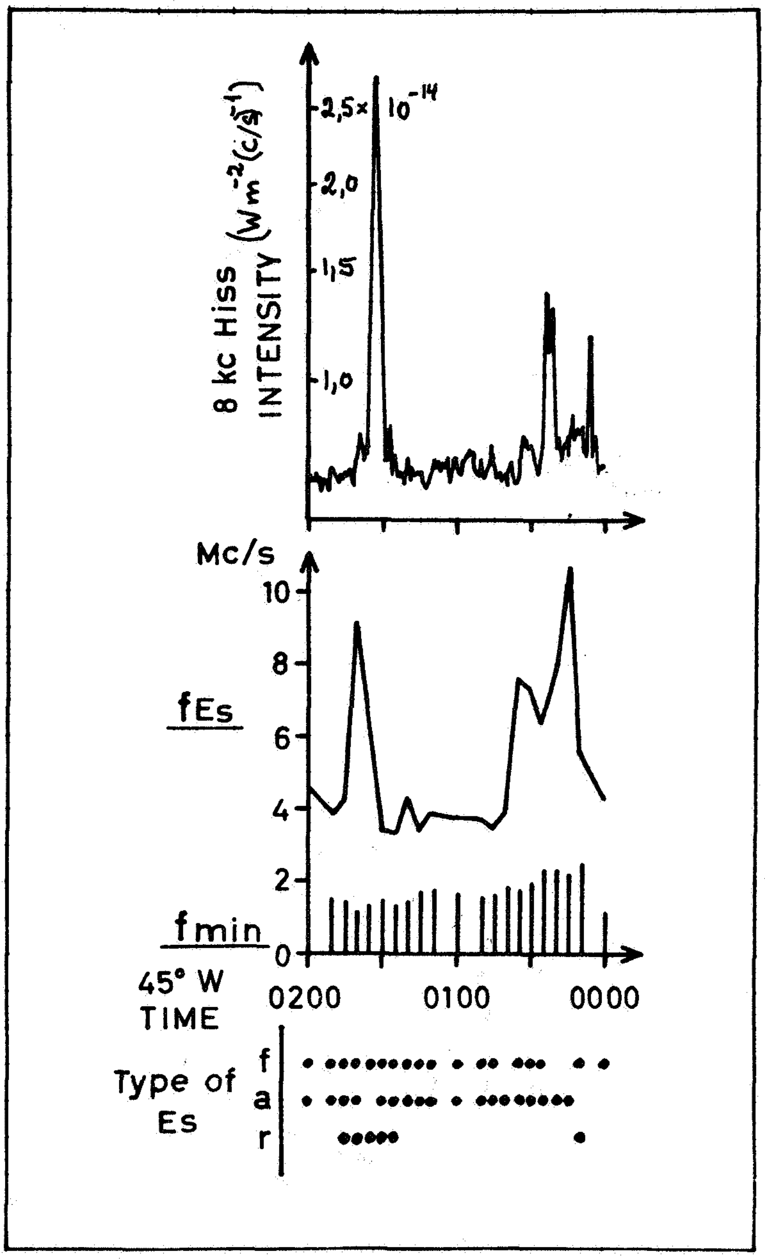

Ap
50
40
30
20
10
0
1 10 20 1 10 20 1 10 20 1 10 20
Number of taperecordings containing HISS in Godhavn
20
10
0
1 10 20 1 10 20 1 10 20 1 10 20
OCT
NOV
DEC
JAN
1962
1963

Figure 5



8 kc Hiss
INTENSITY $(Wm^{-2}(c/s)^{-1})$
2,5 × 10^{-14}
2,0
1,5
1,0
Mc/s
10
8
6
4
2
0
fEs
fmin
45° W
TIME
0200
0100
0000
Type of
Es
f
a
r

Figure 6

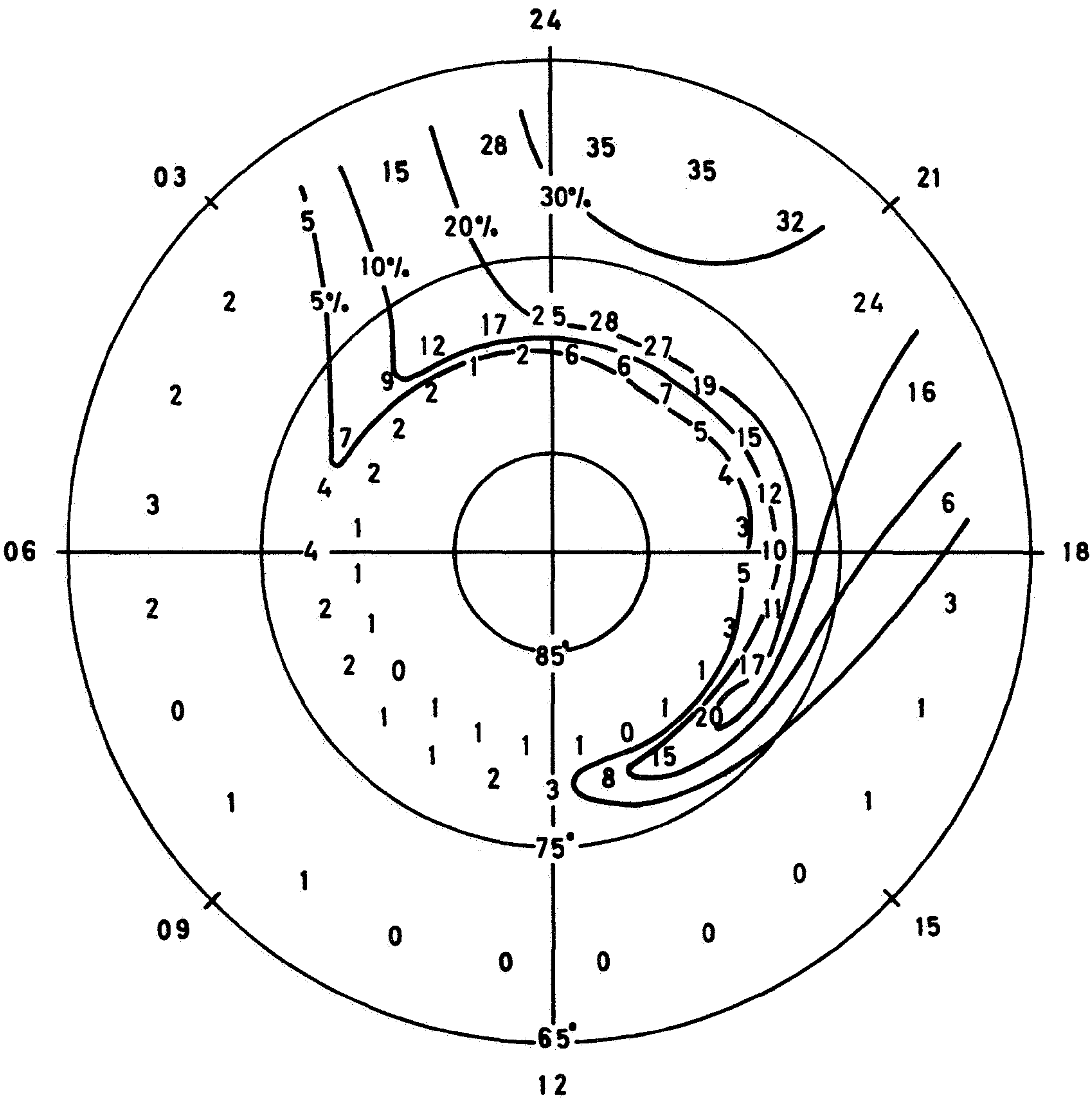


Figure 7

G66-199

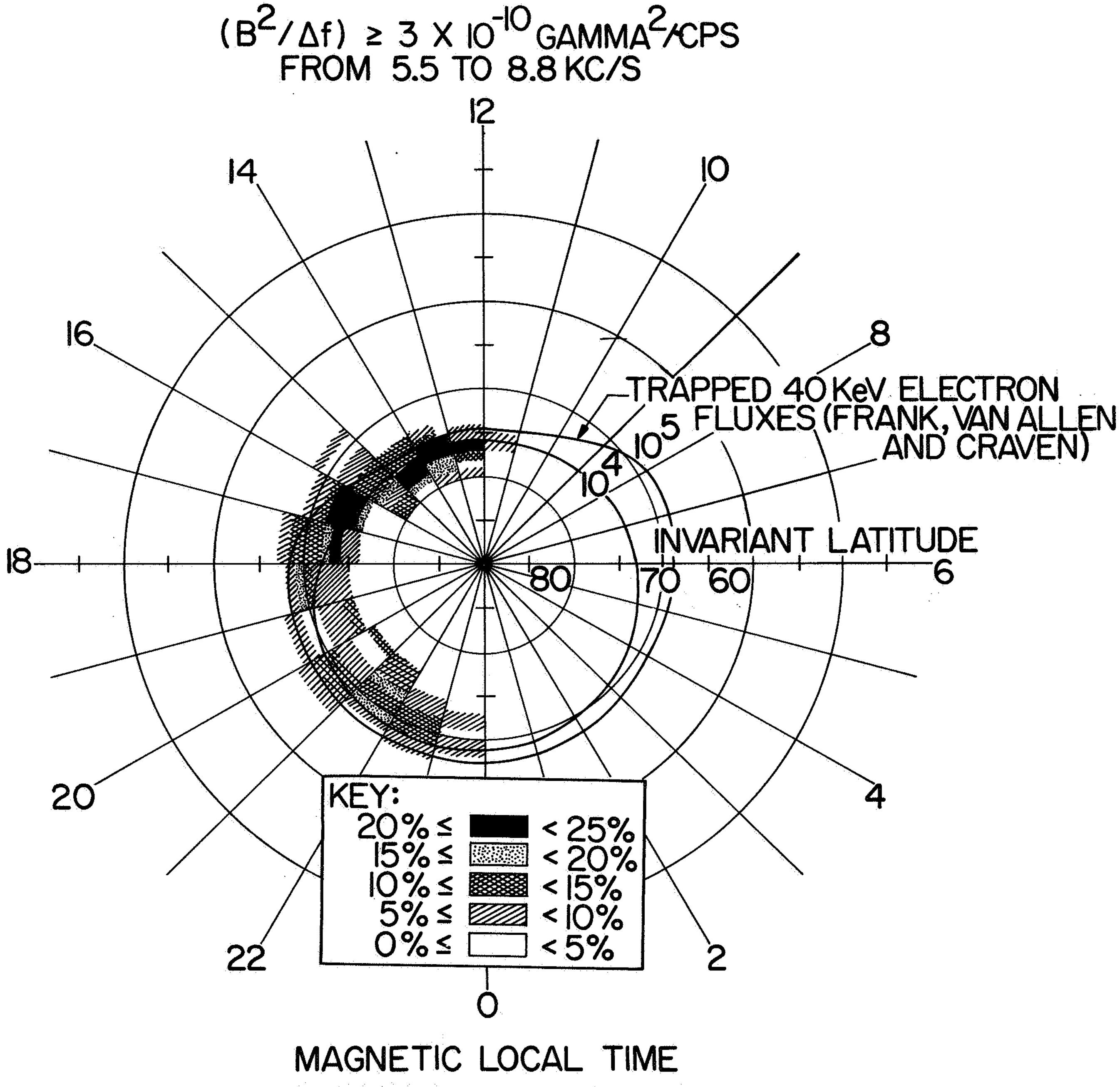
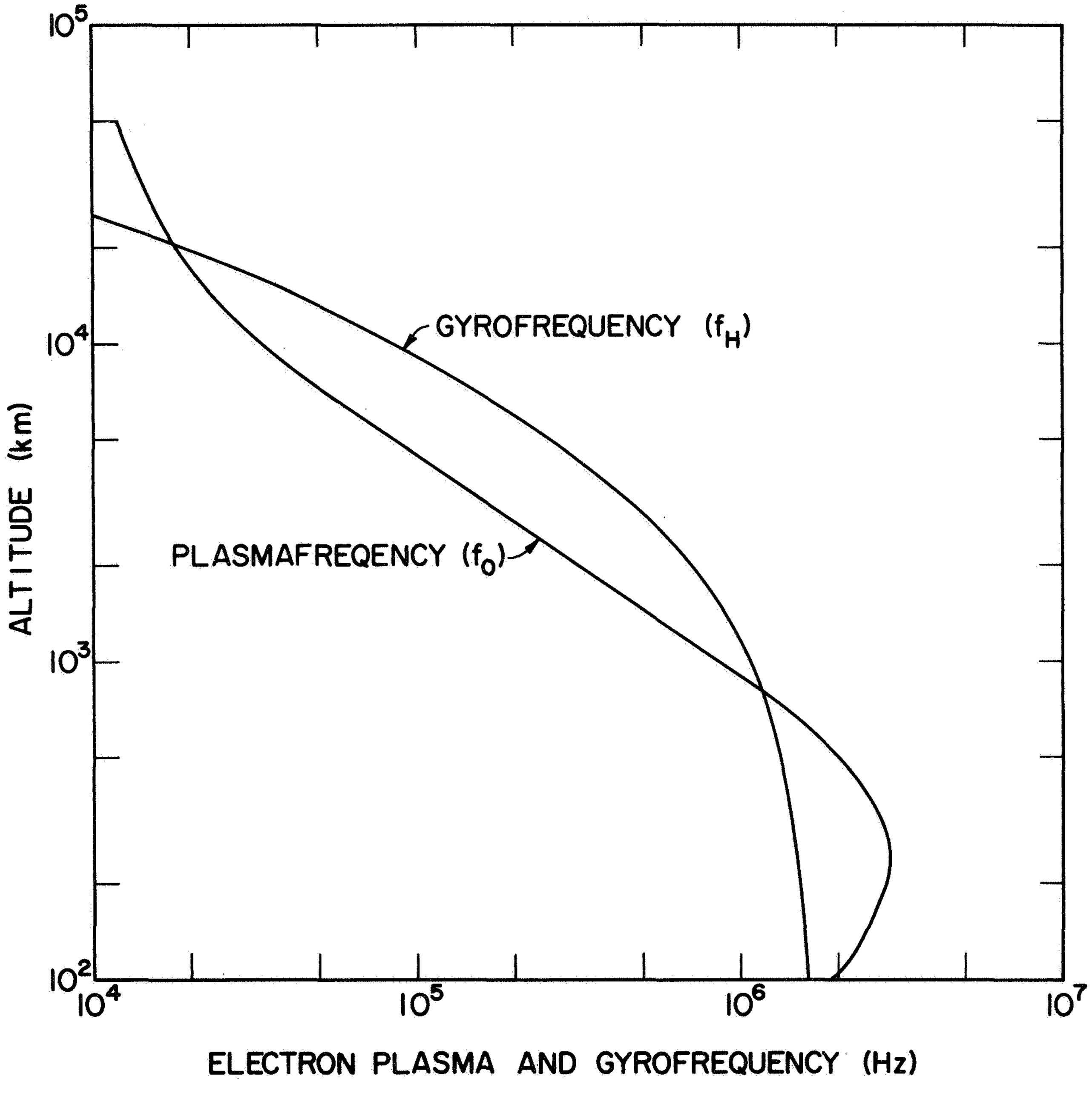
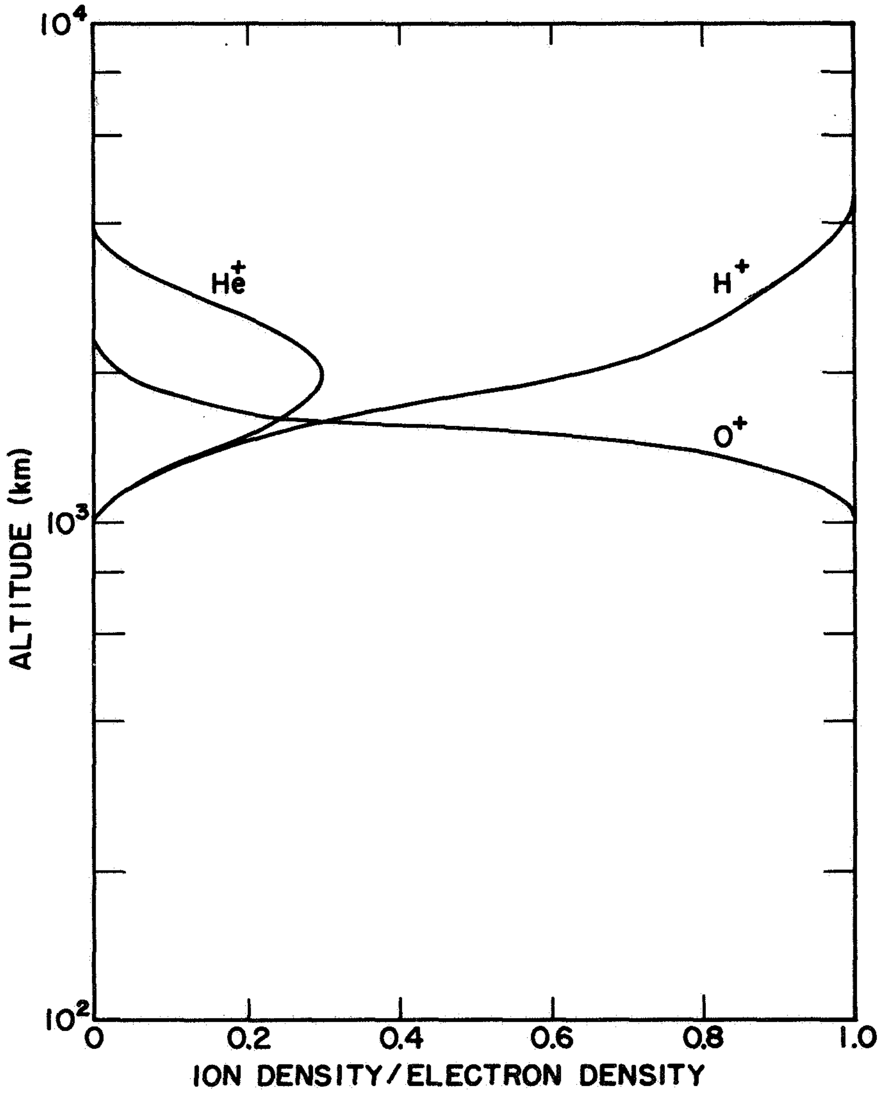


Figure 8



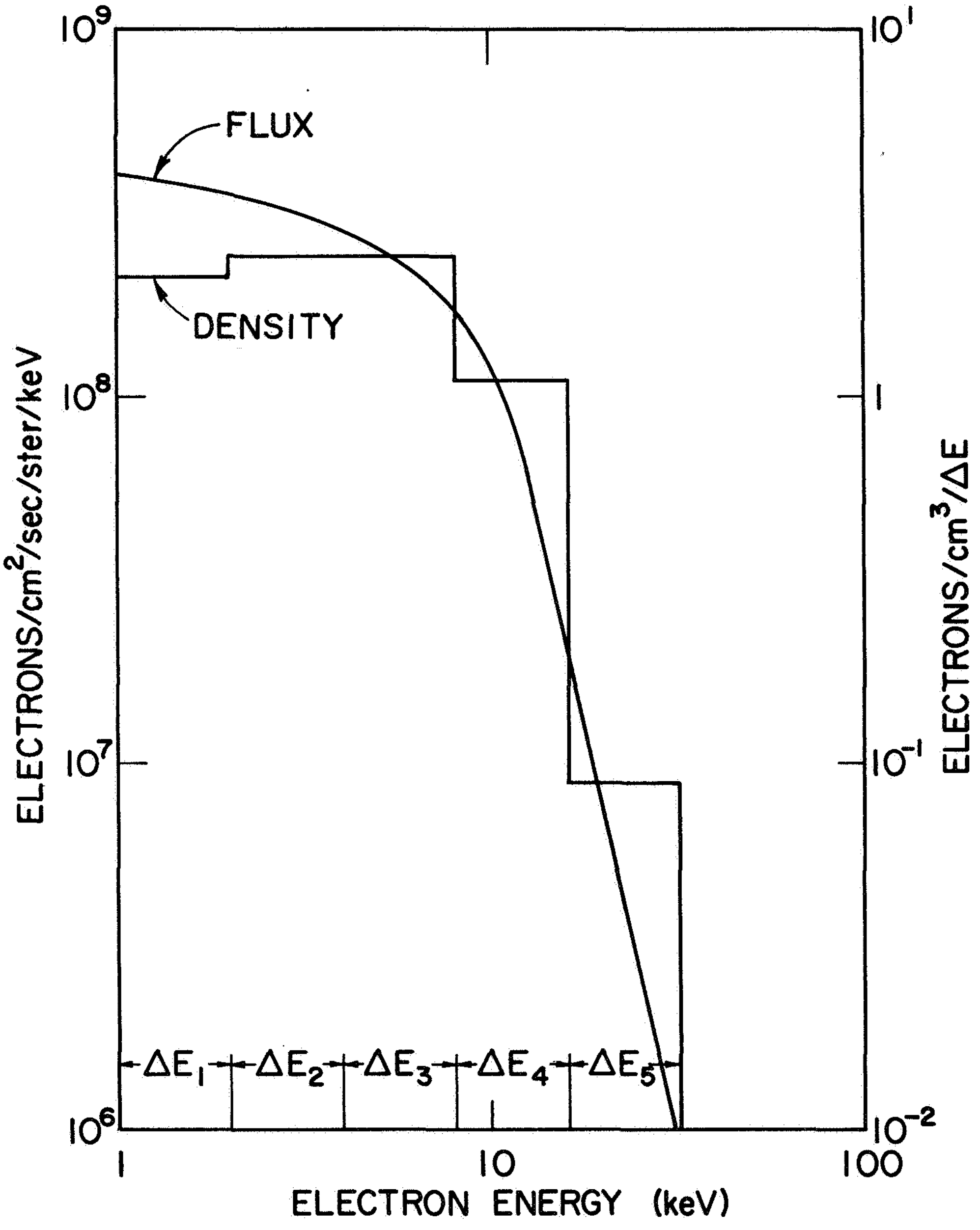
GYROFREQUENCY (f_H)
PLASMAFREQENCY (f_0)
ALTITUDE (km)
10^5
10^4
10^3
10^2
10^4
10^5
10^6
10^7
ELECTRON PLASMA AND GYROFREQUENCY (Hz)

Figure 9



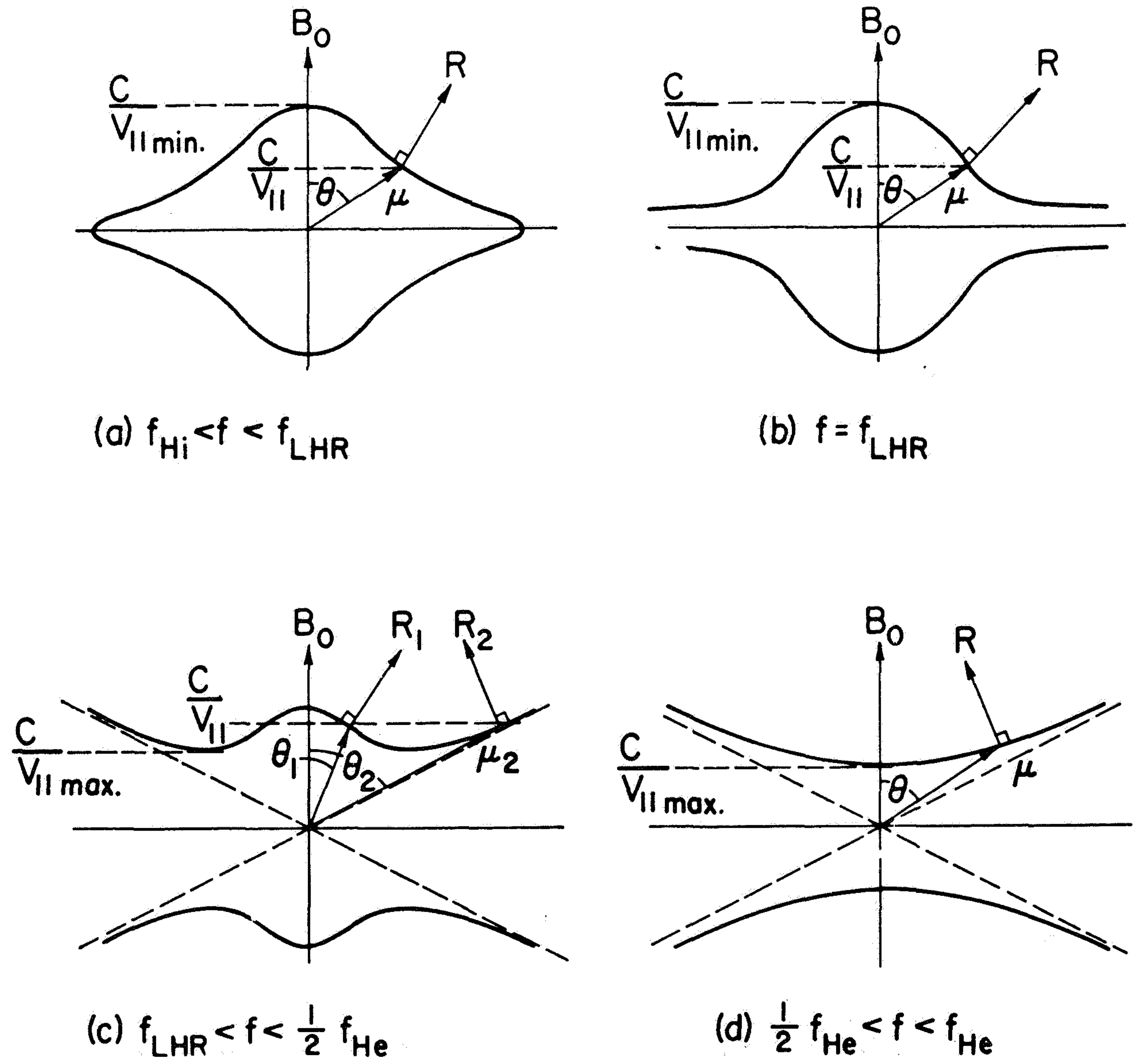
10^4
10^3
10^2
ALTITUDE (km)
He$^+$
H$^+$
O$^+$
0
0.2
0.4
0.6
0.8
1.0
ION DENSITY/ELECTRON DENSITY

Figure 1o



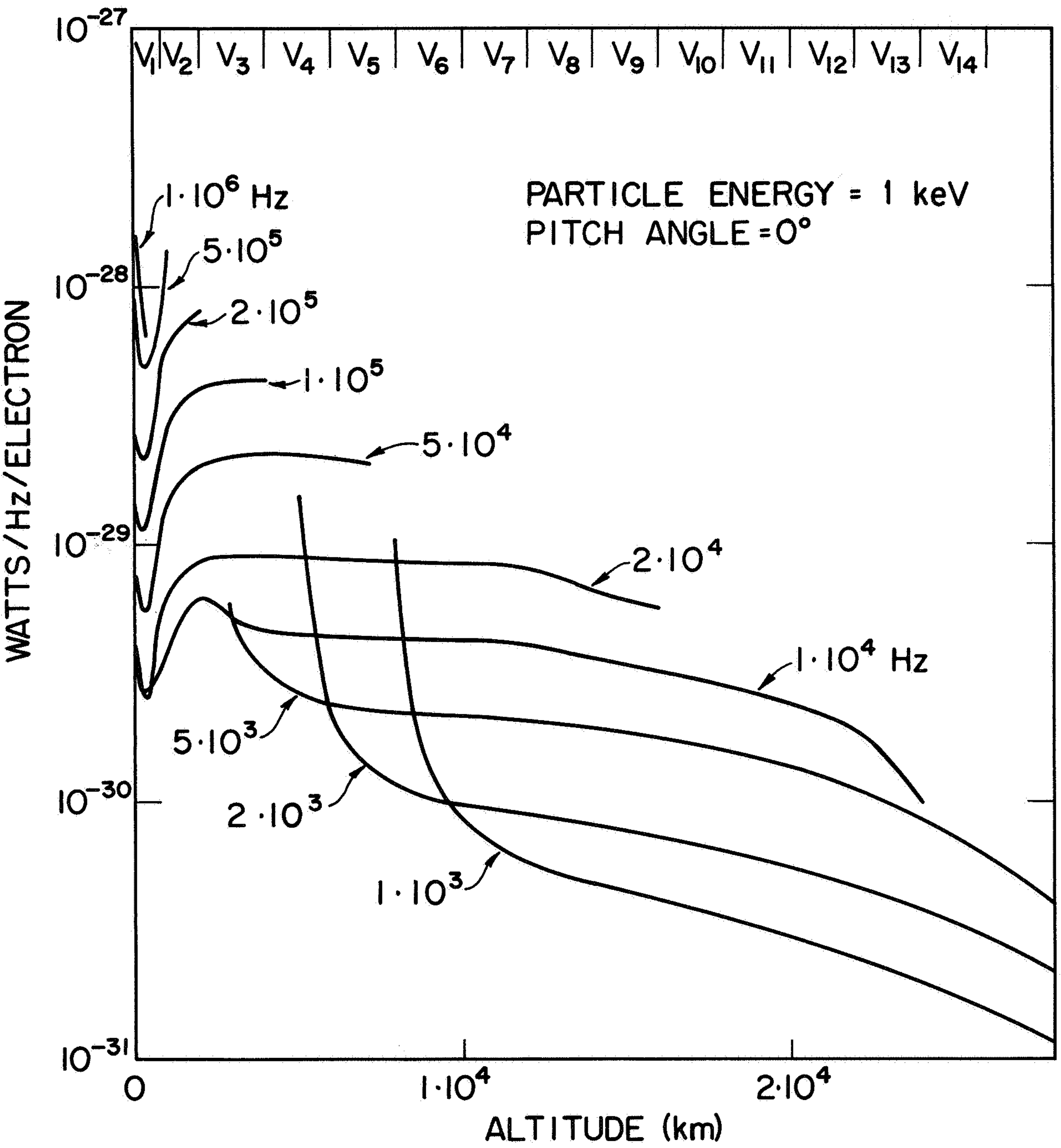
FLUX
DENSITY
10^9
10^8
10^7
10^6
10^1
1
10^{-1}
10^{-2}
ELECTRONS/cm^2/sec/ster/keV
ELECTRONS/cm^3/ΔE
ΔE_1
ΔE_2
ΔE_3
ΔE_4
ΔE_5
1
10
100
ELECTRON ENERGY (keV)

Figure 11



B_o
R
$\frac{C}{V_{\parallel\,min.}}$
$\frac{C}{V_{\parallel}}$
θ
μ
(a) $f_{Hi} < f < f_{LHR}$
B_o
R
$\frac{C}{V_{\parallel\,min.}}$
$\frac{C}{V_{\parallel}}$
θ
μ
(b) $f = f_{LHR}$
B_o
R_1
R_2
$\frac{C}{V_{\parallel}}$
$\frac{C}{V_{\parallel\,max.}}$
θ_1
θ_2
μ_2
(c) $f_{LHR} < f < \frac{1}{2} f_{He}$
B_o
R
$\frac{C}{V_{\parallel\,max.}}$
θ
μ
(d) $\frac{1}{2} f_{He} < f < f_{He}$

Figure 12



PARTICLE ENERGY = 1 keV
PITCH ANGLE = 0°
V_1 V_2 V_3 V_4 V_5 V_6 V_7 V_8 V_9 V_{10} V_{11} V_{12} V_{13} V_{14}
$1\cdot10^6$ Hz
$5\cdot10^5$
$2\cdot10^5$
$1\cdot10^5$
$5\cdot10^4$
$2\cdot10^4$
$1\cdot10^4$ Hz
$5\cdot10^3$
$2\cdot10^3$
$1\cdot10^3$
WATTS/Hz/ELECTRON
10^{-27}
10^{-28}
10^{-29}
10^{-30}
10^{-31}
0
$1\cdot10^4$
$2\cdot10^4$
ALTITUDE (km)

Figure 13

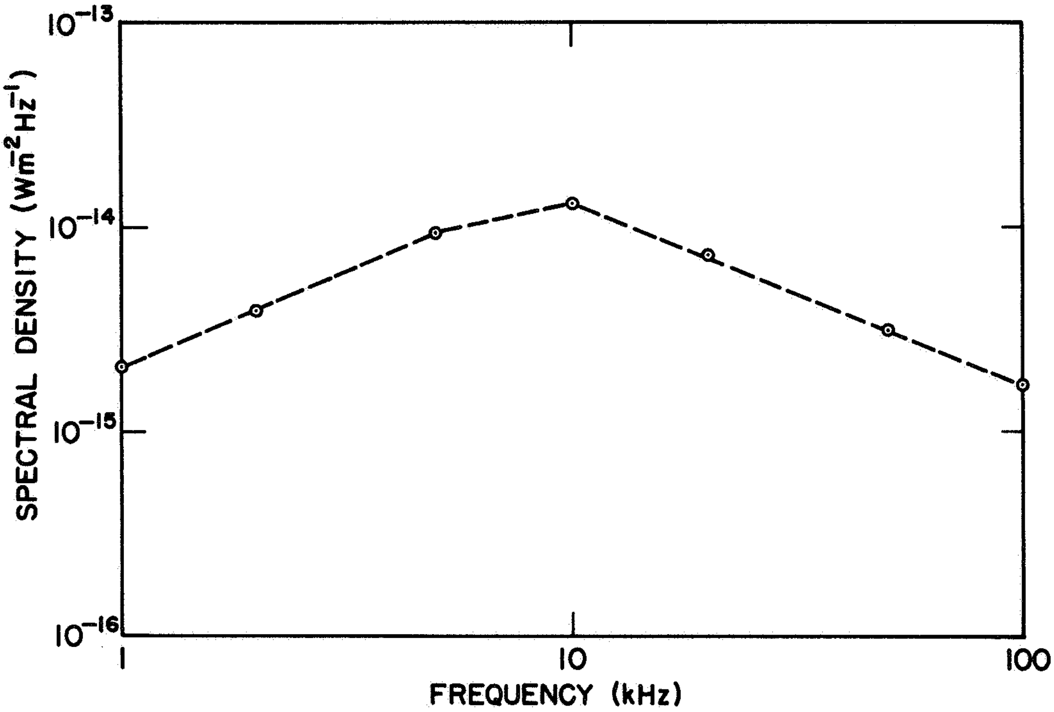

10^{-13}
10^{-14}
10^{-15}
10^{-16}
SPECTRAL DENSITY ($Wm^{-2}Hz^{-1}$)
1
10
100
FREQUENCY (kHz)

Figure 14